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Investigation of Wetlands Hydraulic and Hydrological Processes, Model Development, and Application

by R. Walton, T. H. Martin, Jr., R. S. Chapman, J. E. Davis

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CP	Critical Processes	RE	Restoration & Establishment
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Investigation of Wetlands Hydraulic and Hydrological Processes, Model Development, and Application

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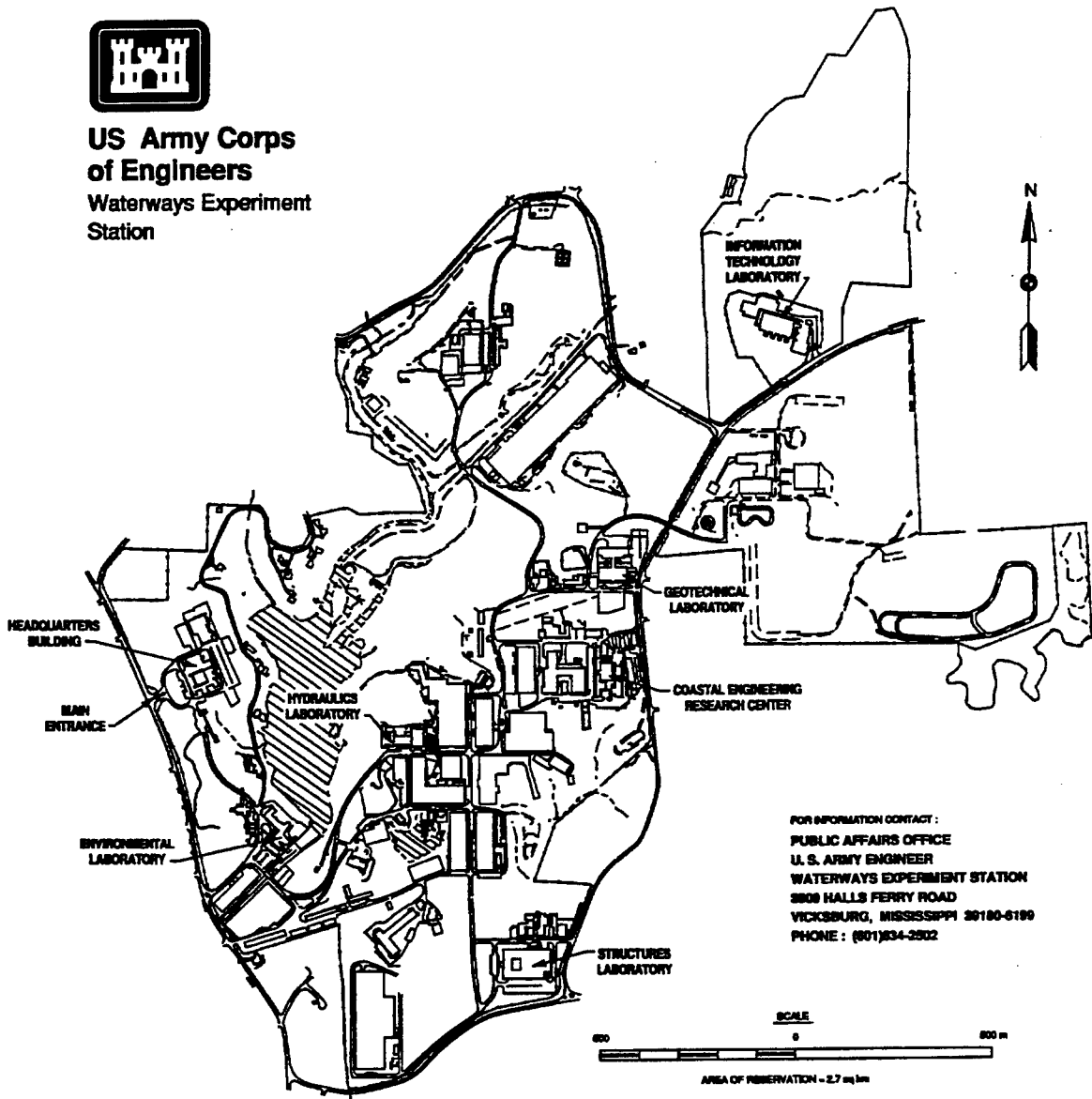
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Hydraulics and Hydrology

Investigation of Wetlands Hydraulic and Hydrologic Processes, Model Development, and Applications (TR-WRP-CP-6)

ISSUE:

Water availability and the processes by which it moves are critical to the quantity and quality of functions provided by wetlands. To effectively evaluate, manage, restore, create, and protect wetlands, the hydrology of a wetland must be understood, and consequently, a capability to quantitatively estimate the wetland's hydrology is necessary.

RESEARCH:

The major hydraulic and hydrologic processes were identified for most wetland types. The water budget and hydraulic processes were evaluated for the Black Swamp wetlands on the Cache River in Arkansas. A Wetlands Dynamic Water Budget Model was developed based on existing model methodologies and algorithm and the program was applied to the Cache River wetlands.

SUMMARY:

The Black Swamp wetlands were monitored during the Wetlands Research Program. Evaluations show that the system is primarily influenced by river flows and that the wetlands were

flooded by the backwater created by downstream constrictions. In conjunction with model simulations, analyses were used to develop hydroperiod information for wetlands based on long-term data at an upstream gauge. The computer program has surface water, vertical processes, and horizontal groundwater flow modules. The model is simple, efficient, and flexible and was most effective in simulating long periods. Model simulations showed the effect of the downstream constrictions on inundating the upstream wetlands.

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Preface

The work described in this report was authorized by Headquarters, U.S. Army Corps of Engineers (HQUSACE), as part of the Critical Processes Task Area of the Wetlands Research Program (WRP). The work was performed under Work Unit 32751, "Critical Processes: Hydraulics and Hydrology," for which Mr. Jack E. Davis, U.S. Army Engineer Waterways Experiment Station (WES), Coastal Engineering Research Center (CERC), was Technical Manager. Mr. John Bellinger (CECW-P:O) was the WRP Technical Monitor for this work.

Mr. Dave Mathis (CERD-C) was the WRP Coordinator at the Directorate of Research and Development, HQUSACE; Dr. William L. Klesch (CECW-PO) served as the WRP Technical Monitors' Representative; Dr. Russell F. Theriot, WES, CERC, was the Wetlands Program Manager. Mr. Davis was the Task Area Manager.

This report was prepared by Dr. Raymond Walton, WEST Consultants, Inc.; Dr. Raymond S. Chapman, Chapman & Associates; Mr. Thomas H. Martin, Forest Wheeler Environmental Corporation; and Mr. Davis, Coastal Structures and Evaluation Branch (CSE), Engineering Development Division (EDD), under the general supervision of Ms. Joan Pope, Chief, CSE, CERC, and Mr. Thomas Richardson, Chief, EDD, CERC. Mr. Charles Calhoun was the Assistant Director, CERC, and Dr. James Houston was Director, CERC.

At the time of publication of this report, the Director of WES was Dr. Robert W. Whalin. The Commander was COL Bruce K. Howard, EN.

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1 Introduction

Researchers have found that hydrology and the dynamic nature of water flowing through wetlands affects the vegetation (composition, structure, and diversity), influences its primary productivity, controls its organic accumulation, and drives its nutrient cycling (Gosselink and Turner 1978). The hydrology of a wetland influences the homogeneity or heterogeneity of the landscape, from varied topographic relief and vegetative cover to broad monotypically vegetated flats (Bedlinger 1979). Mitsch and Gosselink (1986) state that "hydrology is probably the single most important determinant for the establishment and maintenance of specific types of wetlands and wetland processes," and Nestler and Long (1994) state that most significant wetland functions can be described completely or in part by hydrologic factors. The important influences of hydrology on the character of a wetland is echoed in almost all publications that address the topic of wetland hydrology.

While the importance of hydrology on wetland ecology seems to be fully appreciated, our ability to define the relationship is tenuous. Even if wetland hydrology was well understood, its response would still be difficult to predict. The problem is somewhat rooted in the fact that wetlands are very sensitive to hydrology, i.e., subtle changes in hydrology can cause substantial changes in wetland characteristics (Mitsch and Gosselink 1986). Since our ability to predict wetland hydrology is limited, the problem of relating hydrology and wetland characteristics is compounded.

The Corps of Engineers has the mission of evaluating permits for wetland modifications. An adequate permit evaluation requires that characteristics and response of the wetlands to hydrologic changes be understood. In particular, an evaluation must determine the functions of the wetland and the effect of proposed changes to the wetland on those functions. Wetland functions typically evaluated include, but are not limited to, (a) the alteration of flood flows, (b) the removal, retention, and stabilization of sediment from water, (c) the groundwater recharge and discharge, and (d) wildlife and aquatic habitat (Adamus et al. 1991). For the Corps of Engineers to effectively accomplish its mission, it must have tools and techniques for wetland evaluations that are quick and accurate.

The U.S. Army Corps of Engineers established in its Wetlands Research Program (WRP) investigations of the physical hydrologic processes of

wetlands and the influence of those processes on wetland functions. The goal of the research was to further our understanding of those processes and develop a suite of techniques and tools that can be applied in reconnaissance level wetland evaluations or detailed scientific investigations. The research included participation in a comprehensive study of a riverine bottomland hardwood wetland, a general investigation of hydraulic and hydrologic wetland processes, the development of a dynamic water budget model, and the exploration of simplified techniques for assessing hydrologic characteristics of wetlands. This report details the results of these investigations.

The field study was conducted in the wetlands found along the lower reaches of the Cache River between Patterson and Cotton Plant, AR. The Cache River is an underfit stream with wetlands predominantly located in abandoned channels and backswamps. The study area covered approximately 350 square km with about 60 square km containing bottomland hardwood forests (Kleiss 1993).

The hydrologic measurements in the field study included United States Geological Survey (USGS) river gauges at the upstream and downstream limits of the study area (49 river km apart), water level recorders inside the study area, a nest of deep and shallow groundwater wells which monitored variations in the underlying aquifer, a meteorological recording station that collected precipitation, temperature, and solar radiation data inside the study area, and regional precipitation data. The data were analyzed to provide information about the hydrology of the Cache River wetlands in a form useful to other researchers. The analyses also help to characterize the hydrology of floodplain wetlands such as those typical of the Lower Mississippi Valley. The results of the analyses are reported here with a summary of the hydrologic data collected at the site.

The field study results are complimented by a discussion of wetland water budgets and hydroperiods. Investigations of wetland hydrology usually focus on these two hydrologic characteristics. A water budget balances water inflows, outflows, and the gain or loss of stored water in the wetland. The elements of a water budget include precipitation, evapotranspiration, channelized flow, overland flow, groundwater recharge and discharge, tides, and storage capacity. An accurate investigation of a wetland's water budget can help identify the dominant hydrologic mechanisms for that wetland. However, Brinson (1993) provides an example of an oxbow lake where the dominant mechanism is not so obvious. An oxbow system may be dominated by river flow during a flood but dominated by groundwater recharge or discharge, evapotranspiration, and precipitation during drier periods (i.e., a depressional wetland).

While a water budget can indicate the dominant hydrologic components for a wetland, it does not provide information about the dynamic nature of the hydrologic system. The second important hydrologic characteristic of a wetland or region of a wetland is the hydroperiod. The hydroperiod provides information about the depth of flooding, duration of flooding, and possibly the

frequency-of-occurrence of flooding for a given location. While the water budget gives an observer an idea about the nature of the wetland (e.g., a riverine wetland versus a depressional wetland), the hydroperiod helps illuminate where you might expect to find certain species of plants, for example, because their locations may depend on the depth, duration, and timing of flooding.

A dynamic water budget model was developed during these investigations to help determine wetland water budgets and hydroperiods by simulating the temporal and spatial variations of hydrology within wetlands. The model was verified and calibrated to the Cache River data set and was applied during the investigations to provide synthetic data where field data were lacking. This information was particularly useful for those researchers studying large regions of wetlands for habitat or vegetation distributions.

The model has three modules which dynamically simulate surface water processes, vertical flow processes, and horizontal groundwater flow (essentially the components of water budget). The model is based on an explicit link-node technique and incorporates many of the algorithms and solution methods found in existing models (Table 1). The model is relatively simple, efficient, and flexible and can be used to simulate the long-term periods often needed in wetlands research. The model was tested during its application to the Cache River wetlands where the surface water processes dominated. However, the model is designed to simulate other wetland types, such as prairie potholes, where vertical processes and horizontal groundwater flow are likely to dominate, and tidal wetlands.

Table 1 Models Used In the Wetlands H&H Model Development		
Model	Process	Reference
DEM	Surface water link-node	Walton et al. (1989) Hales et al. (1990)
DYNHYD5 (WASP4)	Surface water link-node	Ambrose et al. (1988)
DHM	Surface water diffusion wave	Hromadka and Yen (1986)
HELP	Infiltration and evapotranspiration	Schroeder et al. (1988)
SPUR	Infiltration and evapotranspiration	Wight and Skiles (1987)
Rutter Model	Canopy interception	Rutter, Morton, and Robbins (1975)
MODFLOW	Horizontal groundwater flow	McDonald and Harbaugh (1988)
PORFLO-3	Variably saturated groundwater flow	Sagar and Runchal (1990)
SHE	All processes	Abbott et al. (1986)

Another goal of the hydrologic investigations of wetlands was to develop simple, effective techniques that can be used to study and evaluate wetlands. Hence, the measured and simulated Cache River data were used to evaluate some simple hydrologic evaluation techniques. For example, a water budget analysis was used to quickly highlight the important processes in the Cache River wetlands, and a regression analysis demonstrated the possibility of determining hydroperiods for locations throughout the wetlands based on the long-term record of the upstream USGS river gauge.

The subsequent chapters in this report are structured in the following way: Chapter 2 discusses wetland hydrologic and hydraulic (H&H) processes and general data sources available for acquiring pertinent information; Chapter 3 presents a detailed review and analysis of hydrologic and hydraulic data collected in the Cache River study; Chapter 4 presents the development of the Wetlands Dynamic Water Budget Model; Chapter 5 describes the model's verification tests; Chapter 6 presents a useful computer driven tutorial on how to apply the Wetlands Dynamic Water Budget Model; Chapter 7 highlights the application of the Wetlands Dynamic Water Budget Model to the Cache River wetlands with sensitivity analyses and system modification scenarios; Chapter 8 presents how simplified methods can be developed and used to evaluate general wetland processes, and discusses future needs in wetland hydrologic and hydraulic research, particularly as a follow on to the research reported here; Chapter 9 provides a summary, and Chapter 10 provides report references.

2 Wetlands Hydraulic and Hydrologic Processes

The H&H processes by which water is introduced, temporarily stored, and removed from a wetland is commonly known as the water budget. Water is introduced to a wetland through direct precipitation, overland flow (or runoff), channel and overbank flow, groundwater discharge, and tidal flow. Temporary storage includes channel, overbank, basin, and groundwater storage. Water is removed from the wetland through evaporation; plant transpiration; channel, overland, and tidal flow; and groundwater recharge.

The importance of the above processes varies with wetland type and depends on regional factors such as climate, geology, and physiography. In particular, the physiography or topographic and bathymetric variations in and around a wetland affects the residence time within a wetland, which can increase or decrease the impact of an H&H process. For example, the water budget of riverine wetlands with residence times on the order of hours to days is primarily controlled by differences in channel and overbank inflows and outflows. Depressional wetlands on the other hand, which can have residence times ranging from weeks to seasons, have water budgets that depend primarily on direct precipitation, evaporation, transpiration, and groundwater interaction.

Wetland Basin Characteristics

The physiography of a wetland and its surrounding watershed influence both the interaction and importance of individual H&H processes. Basic information about geometric features such as basin length, width, depth, upstream drainage area, the location and physical characteristics of hydraulic structures, and land use is essential to understand the water budget within a wetland. Initial estimates of these physical features can be derived from USGS topographic maps, aerial photography, wetland inventory maps, and National Ocean Survey (NOS) charts for tidal areas. Refinements to the initial estimates can be made from data collected during a field visit. Useful spatial relationships that can be derived using these data are stage-area and stage-volume curves,

which allow the quick estimate of the extent of areal flooding given point surface elevation measurements.

Precipitation

Surface water processes within a wetland are tied to both local and regional precipitation patterns. Precipitation can influence a wetland water budget directly through rain and snowfall within the physical boundaries of the wetland and the associated runoff or indirectly through inflows from upstream watersheds. Information required to estimate the influence of precipitation ranges from regional and seasonal variability to the frequency and magnitude of individual storm events. Complete daily records and statistical summaries of regional meteorological conditions are available through the National Weather Service (NWS).

Evaporation and Transpiration

Surface water loss due to evaporation depends on meteorological conditions (such as air temperature, humidity, and wind speed) and ground conditions (such as vegetative cover and the soil moisture content). Regional estimates of evaporation rates are obtained by pan, lake, and reservoir evaporation studies and are available through the NWS. Pan evaporation rates are higher than for lakes and reservoirs; therefore, as a rough rule, pan evaporation rates should be reduced by 30 percent when applied to open water within a wetland (Kohler 1952).

Transpiration results from root uptake by emergent plants and the subsequent loss to the atmosphere through leaf surface area. Estimates of transpiration rates are related to vegetative density, soil moisture content, and the depth to the deep root zone. Often the effects of evaporation and transpiration on a wetland water balance are combined into a single estimate of water loss called evapotranspiration. Evapotranspiration is a function of meteorological conditions, plant density, and water availability in the soil. A number of process-based and empirical methods for estimating evapotranspiration are available in the literature (Priestley and Taylor 1972, Christiansen 1968, Kadlec, Williams, and Scheffe 1986).

Channel and Overbank Flow

Channel and overbank flow can significantly impact the introduction, temporary storage, and removal of water within all types of wetlands. Flowrates are closely linked to net precipitation and resulting processes such as watershed runoff, ice and snowmelt, and flood flows from upstream watersheds. Estimates can be obtained from USGS stage-discharge relationships derived for

gauged rivers. The influence of channel and overbank flows on wetland processes varies seasonally and yearly in magnitude, duration, and frequency. This variability should be considered when using measured flowrate and stage data to determine the areal extent and duration of flooding within the bounds of a wetland. The USGS publishes mean annual peak flowrates and flood flow events for selected return intervals (Barnes and Golden 1966) that can be used to view limited field data in a proper statistical perspective. In addition, much of the data compiled on river stage, discharge, and reservoir volumes are available through data systems such as the USGS WATSTORE (National Water Data Storage and Retrieval System) and on CD ROM, which provide daily observations and statistical summaries.

Overland Flow

Overland flow following direct precipitation occurs when the infiltration capacity of the soil is exceeded. The resulting flow follows topographic gradients until it enters a channel or accumulates in a local depression where it will pond, infiltrate, and/or evaporate. Estimates for overland flow can be obtained from methods such as the Rational Formula (Bedient and Huber 1988), which relates discharge to rainfall intensity, watershed area, and losses such as infiltration and detention storage. Data on runoff coefficients for various land coverage types may be obtained from standard reference handbooks (Chow 1964) and the SCS Engineering Field Handbook (Soil Conservation Service (SCS) 1992).

Groundwater Recharge and Discharge

Differences between surface water elevations and the groundwater table can result in groundwater recharge or discharge. Recharge to the aquifer occurs when the surface water elevation exceeds the groundwater table, and discharge occurs with the opposite conditions. Estimates of groundwater discharge can be obtained by applying Darcy's Law for saturated flow (Freeze and Cherry 1979):

$$Q = k_s A_s \frac{\partial H}{\partial z} \quad (1)$$

where

Q = flow

k_s = saturated vertical hydraulic conductivity

A_s = surface area

H = piezometric head above datum

z = vertical distance

The data required to evaluate this process are surface water elevations, groundwater elevations, and properties, such as hydraulic conductivity of the soil or sediment. These data can be obtained from state offices of the USGS and the SCS. Regional groundwater level information is also available through WATSTORE.

Tidal and Related Flows

The impact of the tides on the water budget of a coastal or estuarine wetland varies temporally and regionally because tidal periods and amplitudes exhibit a wide variation from one location to another. Tide tables, tidal current tables, and tidal current charts can be obtained from the National Oceanic Aeronautic Administration (NOAA). Daily information on high and low tides is available in local newspapers. In addition, related flows, such as freshwater inflows, wind-driven currents, and waves can radically alter periodic volume balance and the salinity distribution within a tidal wetland. Estimates of freshwater inflow should include flows gauged upstream of the tidal influence and runoff from contributing watersheds. Methods of estimating variations in water level due to wind forcing are provided in the *Shore Protection Manual* (1984).

3 Cache River Data Analysis

Introduction

As part of the WRP, significant H&H data have been collected in the Black Swamp wetlands of the Cache River, Arkansas. In this chapter, these data are reviewed, presented, and used to gain insight to the major H&H processes in this wetlands study area.

Background

The Black Swamp wetlands are located on the Cache River in eastern Arkansas (Figure 1). The primary USGS gauging station for monitoring inflows to the study area is located at a highway bridge crossing the Cache River near Patterson. Outflow from the study area is measured at a USGS gauging station at a county-road bridge crossing the Cache River about 9 km north of Cotton Plant. The gauges are about 49 river km apart. Much of the study area has recently become a U.S. Fish and Wildlife refuge, and the area has been designated a RAMSAR site of critical biological importance (Kleiss 1993).

The drainage basin of the Cache River upstream of Patterson is 2,686 square km (Neeley 1987). The study area includes 350 square km of the lower part of the drainage basin and is located about 45 km upstream from the confluence with the White River. Approximately 60 square km of the study area are bottomland hardwood forests and are typical of wooded wetlands systems in the lower Mississippi River Valley (Kleiss 1993). The wetlands generally lie within 2 km of the river channel.

The Cache River is an underfit stream, flowing in an old channel of the present-day Black and St. Francis rivers. It is located in the western lowlands region of the Mississippi River Alluvial Plain, between the Ozark Plateau and the Mississippi River. The wetlands in the basin are predominantly located in the abandoned channels and backswamps. Much of the Cache River upstream of the study area has undergone extensive channelization to allow agricultural development in the basin.

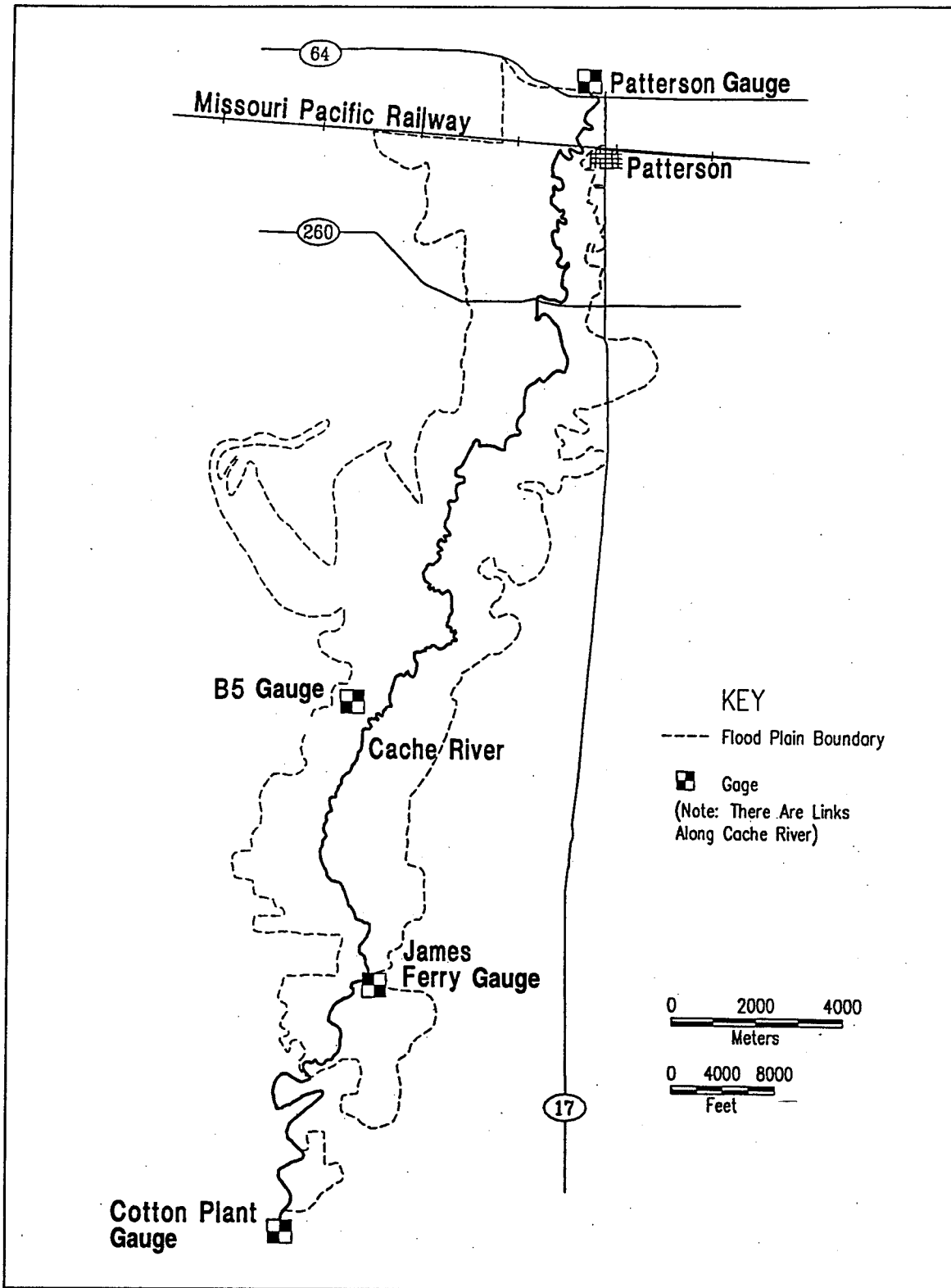


Figure 1. Black Swamp wetlands on Cache River, Arkansas

Objectives

The analyses presented are part of the overall study of the Black Swamp. The objectives of the analyses are to present and summarize the H&H data in a manner useful for other wetland scientists and to provide data in a useful form for calibrating and applying the Wetlands Dynamic Water Budget Model. The analyses attempt to characterize the Cache River system, to identify major H&H processes, and to understand the mechanisms that control these processes.

Approach

The wetland H&H processes are controlled by meteorology, system geometry, river flows and stages, soils, and groundwater dynamics. Sources of these data were identified and the information obtained. These data are presented in a variety of ways, either for the entire period of record, or for shorter periods to illustrate some aspect of the record and system. Finally, a number of data analyses were performed to gain insight into how the system functions. The analyses included correlations of river stage and discharge, an examination of the water balance of the wetlands, a study of the major H&H processes, determination of some overall basin properties, and an analysis of hydroperiods based on upstream gauge data at Patterson.

Data Reviewed

The data obtained, presented, and used for the analysis of H&H processes in the Black Swamp fall into five categories: meteorology, system geometry, surface water hydrology (flows and stages), groundwater hydrology, and soils and vegetation. The period of record used for data presentation and analysis was from October 1, 1987 (the start of Water Year (WY) 1988) to September 1993. Times in this report are referenced in days from October 1, 1987.

Meteorologic data

Precipitation data in the form of total daily rainfall were obtained for NOAA weather observation stations at Augusta, Georgetown, Paragould, Wynne, and Brinkley, Arkansas. Figure 2 shows the periods of records used. The distribution of rainfall was nonuniform over the stations, so the local average daily rainfall for the wetland was computed from the data for the stations. The average is an unweighted arithmetic average.

In addition, WES researchers deployed their own weather station in the Black Swamp, and measured hourly air temperature, solar radiation, and wind speed and direction. The data have gaps of a month or more. Figure 2 also shows the period of record used at this station.

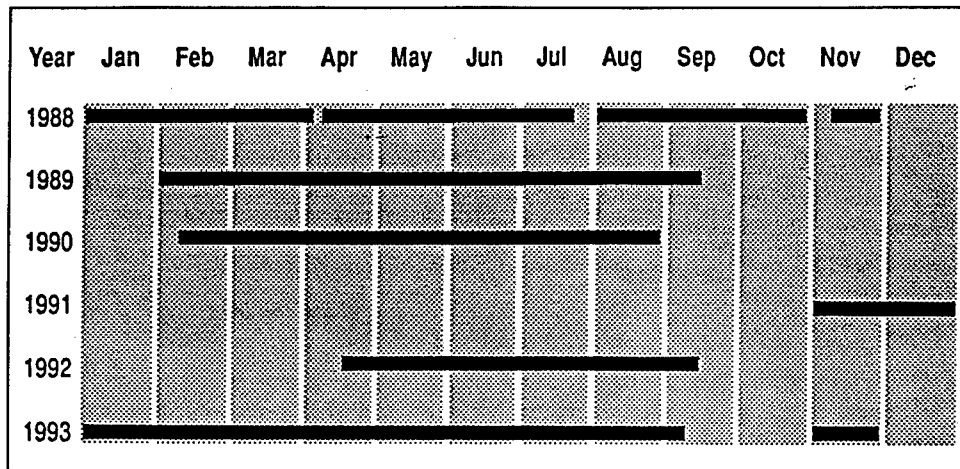


Figure 2. NOAA and Black Swamp weather station periods of record

Geometry

The shape of the wetland has a major influence on H&H processes. USGS topographic maps scaled at 1:24,000 were used to identify large-scale system geometry. In addition, the U.S. Army Engineer District, Memphis, performed detailed cross-sectional surveys of the main channel of the Cache River in this area. The cross sections are shown in Appendix A.

River flows and stages

The U.S. Army Engineer District, Memphis, maintains a permanent gauge at Patterson that records river stage. In addition, at the request of WES researchers, temporary gauges were installed by USGS researchers at James Ferry and Cotton Plant (Figure 1). Figure 3 shows the periods of record used, generally from October 1, 1987, to late September 1993. The James Ferry gauge was operated from October 1989 to October 1992.

As part of the WRP, WES surveyed four transects within the Black Swamp denoted A, B, C, and D. Two continuous stage gauges were installed on the B transect at sites B5 and B8 located approximately 300 m and 660 m over-bank from the main channel, respectively (Figure 1). The gauges provided data from January 1990 to June 1991 (Figure 3). After June 1991, the suite of continuous gauges in the vicinity of the "B Transect" was expanded to four. However, the data are still preliminary and were not used in this presentation and analysis. In addition, discrete stages were periodically observed and recorded on all four transects during the same period.

At the gauge stations at Patterson and Cotton Plant, discharge rating curves were available which provided river flows.

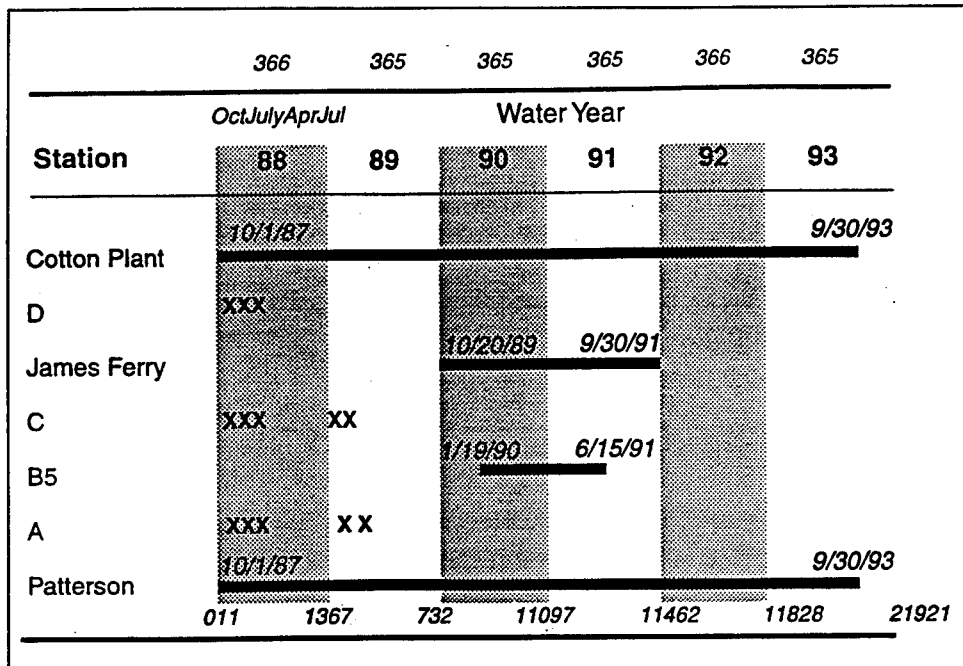


Figure 3. Periods of record used for stage gauges

Groundwater hydrology

The USGS conducted a groundwater study of the Black Swamp (Gonthier and Kleiss 1994). Static heads were measured in the confining unit and underlying aquifer at 121 wells and 13 staff gauges within the wetlands.

In general, the stratigraphy in the area consists of surficial soil and leaf litter overlying a confining unit of clay and silt which is 1.5 to 9 m thick. The base of the underlying sand aquifer is about 27 to 48 m in depth and consists of sands and gravel. For the study, hydraulic conductivities of 0.000042 cm/sec and 0.0007 cm/sec were used for the confining layer and underlying aquifer, respectively.

Soils and vegetation

The Woodruff County Soil Survey (SCS 1968) was reviewed to estimate soil properties and underlying soil horizons. The predominant soils in the wetlands are all listed on the county Hydric Soils list as hydric, i.e., soils that formed under conditions of saturation, flooding, or ponding long enough during the growing season to develop anaerobic conditions in the upper part of the soil profile. They exhibit poor drainage and slow infiltration rates. The soils are classified as *Typic Fluvaquents*, *Typic Ochraqualfs*, *Albic Glossic Natraqualfs*, and *Vertic Haplaquepts*.

As part of the WRP, an extensive database of vegetation types, distributions, densities, and other properties were collected. The data will be presented in detail in other WES reports¹ but are used here for roughness and evapotranspiration calculations. In summary, vegetation in the lowest, most permanently flooded part of the forest consists primarily of tupelo gum (*Nyssa aquatica*) and bald cypress (*Taxodium distichium*). As the elevation increases, the vegetation is typical of the oak/hickory communities in the bottomland hardwood forests in the lower Mississippi Valley. Overcup oak (*Quercus lyrata*) and bitter pecan (*Carya aquatica*) are dominant initially, grading into Nuttall oak (*Q. nuttalli*) and Willow oak (*Q. phellos*), with water oak (*Q. nigra*) and sweet gum (*Liquidambar styraciflua*) dominant at higher elevations. Although there are some differences in stem densities and basal area between the vegetative communities, from a hydrologic viewpoint, the floodplain can be treated as having uniform roughness due to vegetation and responding in a uniform manner to evapotranspiration losses.

Data Presentation

Meteorology

Figure 4 shows a time series of average-daily rainfall computed as a simple, unweighted average of the "local" NOAA station daily data and the daily rainfall observed at the meteorological station located in the Black Swamp. Figure 5 shows an example of the variability between stations, including the onsite wetlands station, for October 1987. This variability is typical of the climatology of the region which is characterized by localized thunderstorms.

The air temperatures at the onsite wetlands station were analyzed to determine maximum and minimum daily values. These values are shown in Figure 6 for the period of record. Maximum daily values of solar radiation are shown in Figure 7.

Geometry

A plan view of the wetlands is shown in Figure 1. The Black Swamp averages about 4 km in width but is constricted in the vicinity of the James Ferry and Cotton Plant gauges.

A longitudinal profile of the Cache River thalweg and channel banks are shown in Figure 8. The steepest parts of the river are upstream above the main wetlands area and downstream below James Ferry where the banks are high. The river flattens out in the main portion of the wetlands downstream.

¹ R. D. Smith. (1994). Personal communication, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

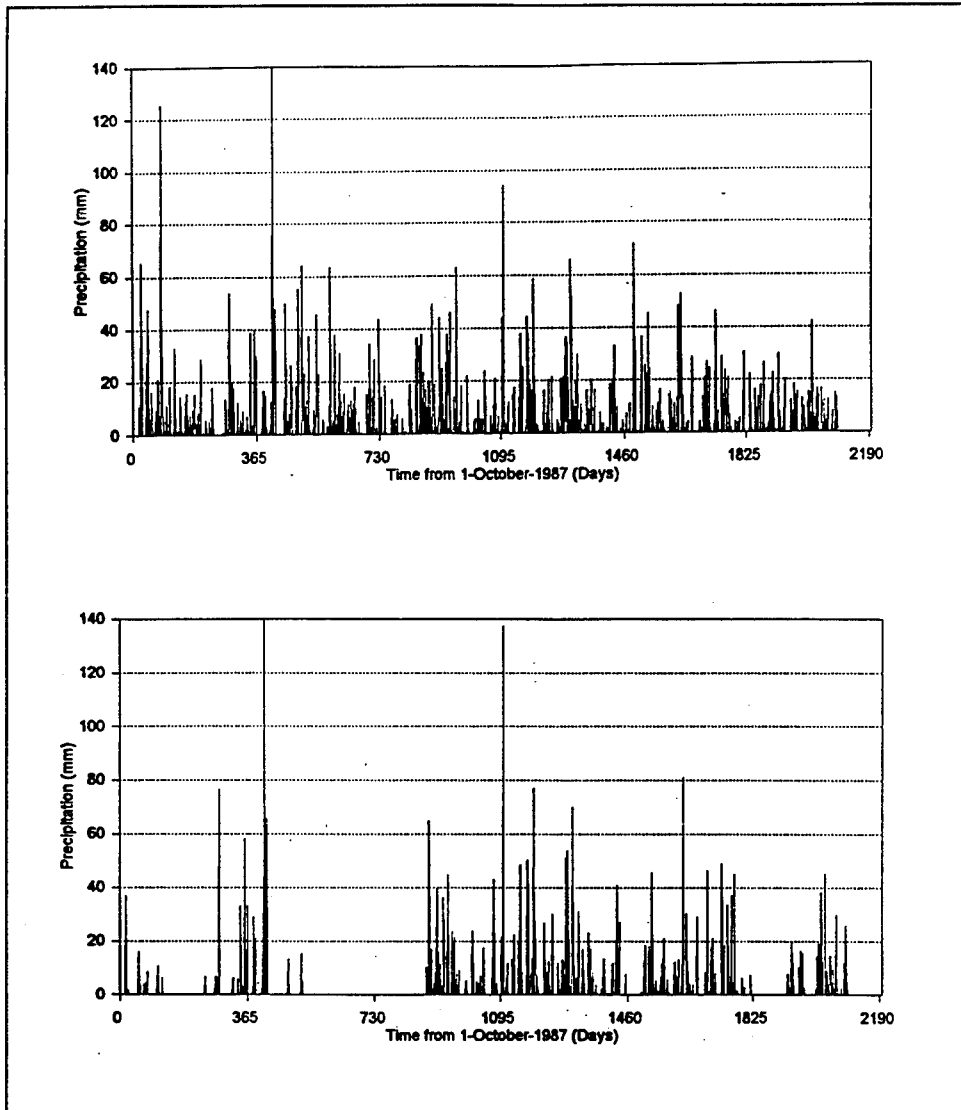


Figure 4. Precipitation at Black Swamp Meteorological Station

The average channel slope is approximately 0.15 m/km. The location of the constriction in the vicinity of James Ferry coincides with an increase in bank elevation relative to the river.

The cross sections, shown in Appendix A, have the same pattern. Upstream and through the constricted region near James Ferry, the sections are relatively narrow with steep banks. In the main wetlands area, the channel is wide and banks are low. Water can easily overflow the channel in this area and travel laterally.

The basin area above the USGS gauge at Patterson is 2,685 sq km; the length is 222 km.

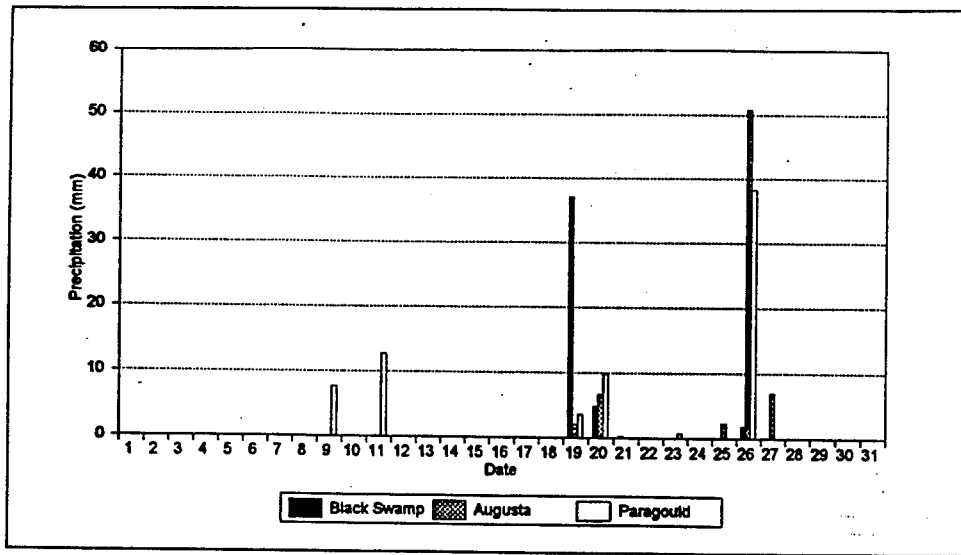


Figure 5. October 1987 precipitation—Cache River watershed

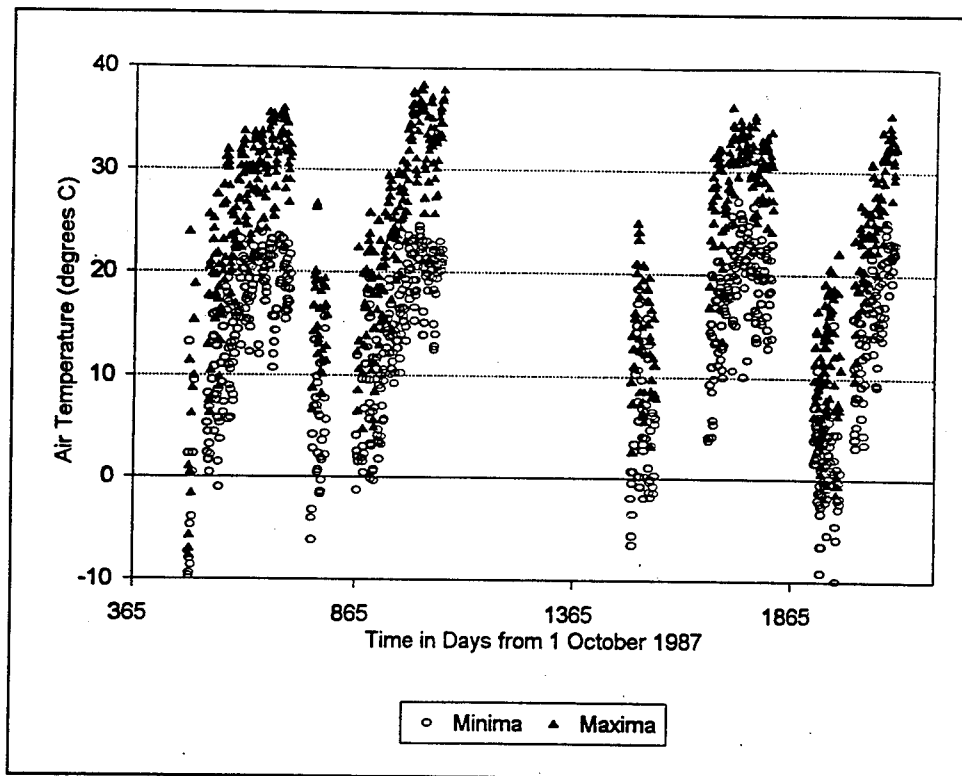


Figure 6. Maximum and minimum daily temperatures at Black Swamp weather station

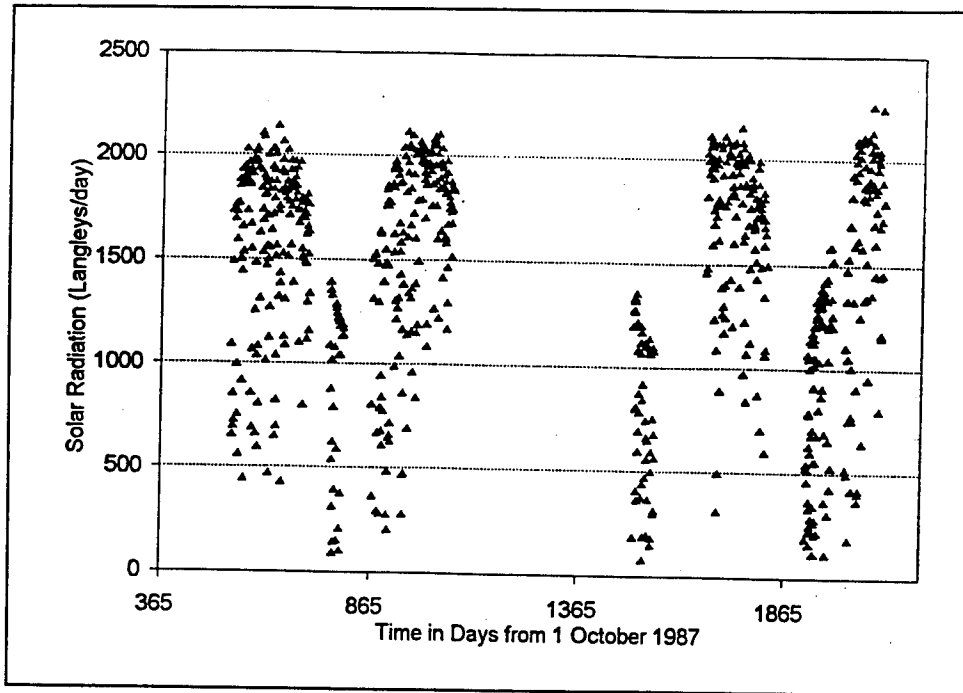


Figure 7. Maximum daily solar radiation at Black Swamp meteorological station

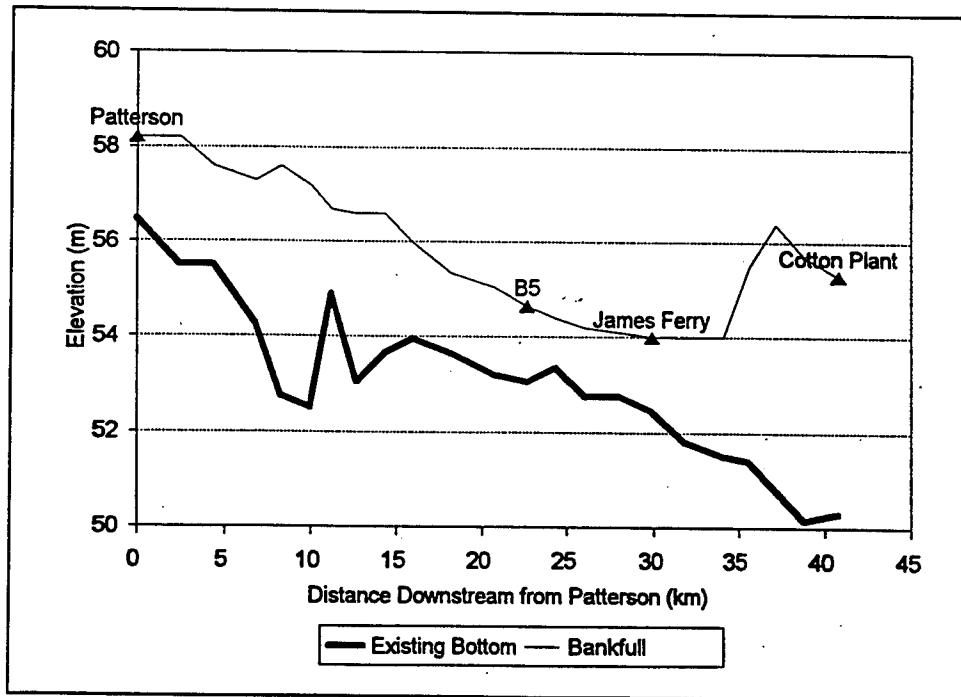


Figure 8. Cache River profiles

River Flows

Mean daily discharges for the USGS gauges at Patterson and Cotton Plant, and the local average daily rainfall, are plotted in Figure 9. The figure shows the wet-dry seasonal cycle, including the rapid rise and recession of the hydrograph at either end of each wet season. The data show that there is a wet season from mid- to late fall to midwinter, and a second wet season in mid- to late spring. During Water Years 1989 and 1991, distinct late-winter dry spells can be seen. In 1991, the discharge receded to summer baseflow levels (about 5 m³/s) by the end of March. In 1989, the discharge did not fully recede until the end of April.

Exceedance curves for the two gauged flows are shown in Figure 10. The median flow (50 percent exceedance) for both gauges is about 25 m³/s. Discharges at Cotton Plant average about 5 percent more than at Patterson. However, this value is about the same as the accuracy of a well-established gauge. Table 2 gives flows for various return periods at the Patterson gauge (USGS 1987).

Return Interval (years)	Flow (m ³ /s)
2	185
5	270
10	328
25	405
50	467
100	529

Individual storm event hydrographs were plotted with local average daily rainfall in Figure 11. The events were selected to show the runoff response to rainfall and have little antecedent or poststorm rainfall. The time base for the dry period storm events ranged from 3 to 4 weeks. This is the time between the initial rise in the hydrograph at Patterson to the time that Cotton Plant recedes to baseflow. The lag time between the peaks of the hydrographs at Patterson and Cotton Plant ranges from 4 to 8 days. The mean reduction in peak flow is about 20 percent.

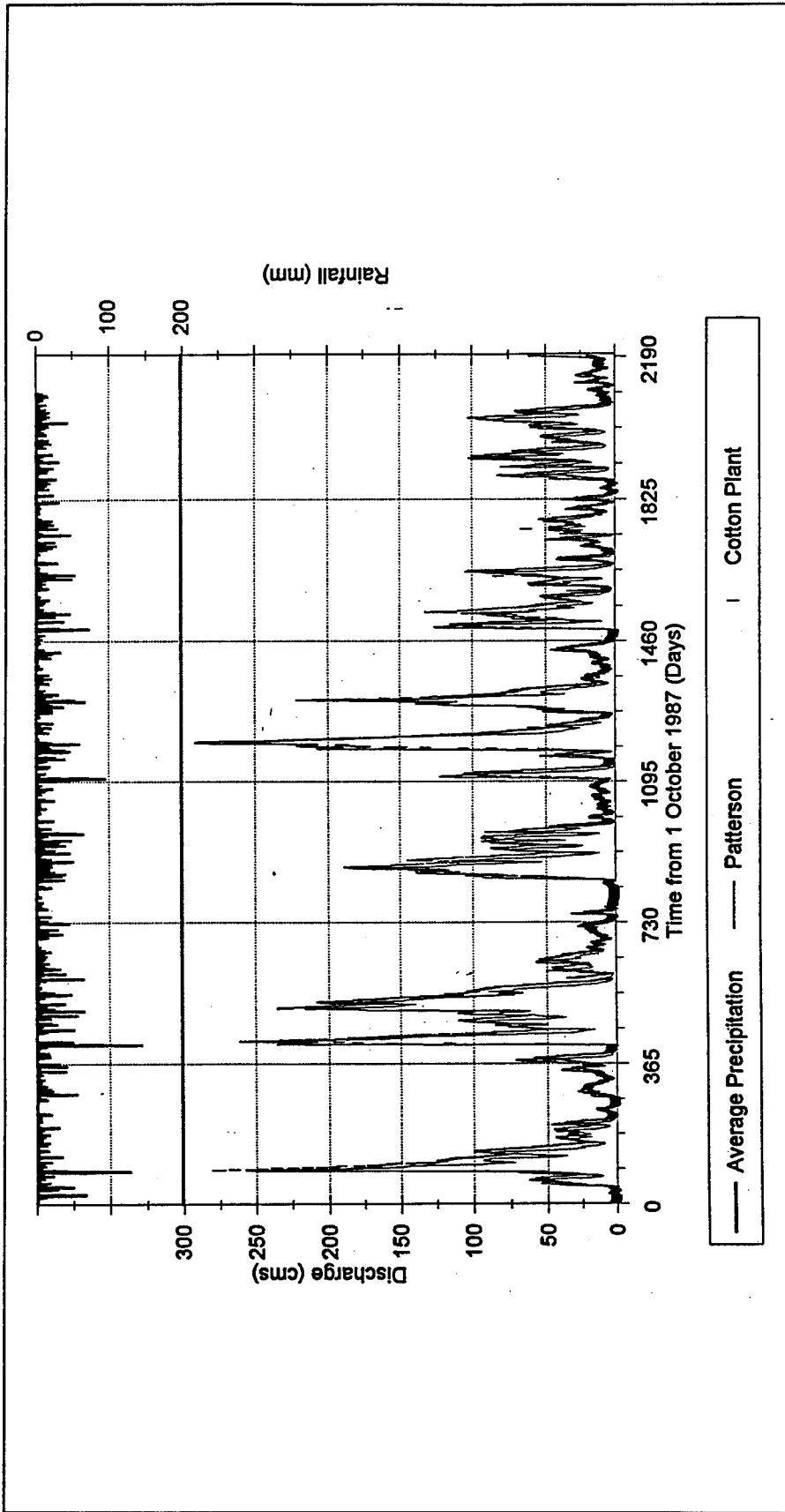


Figure 9. Discharge and rainfall for Water Years 1987 to 1993

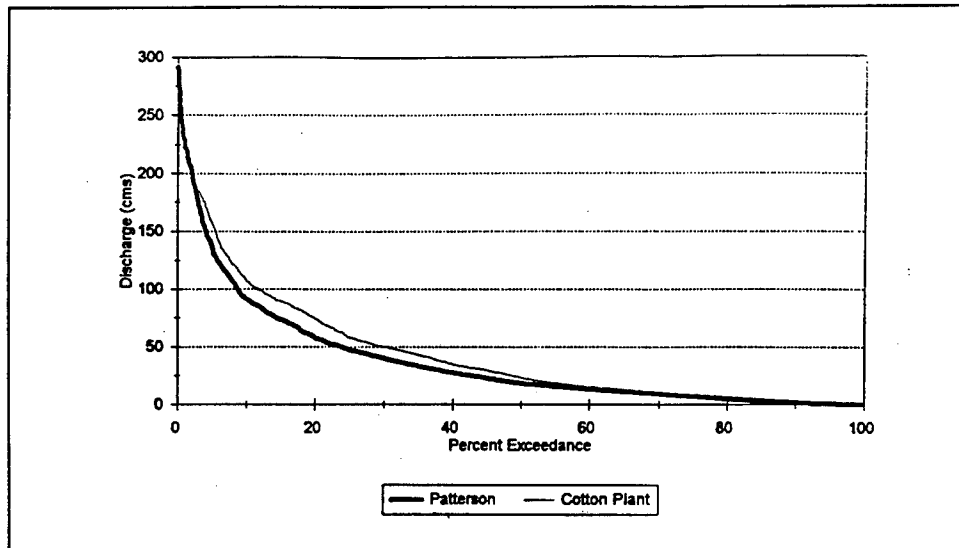


Figure 10. Percent flow exceedance

The wet season hydrograph shows a cumulative response to frequent rainfall events. For example, the winter wet season in Water Year 1991 lasted about 10 weeks (Figure 12). The storm event of 19 December 1990 caused the initial rise, and then many periods of rainfall followed, with about 60 mm occurring in January 1991. Events with less rainfall, however, do create a response in the observed hydrographs, unlike similar rainfall amounts falling during the dry season. The largest event during this period resulted in a 2-day lag between Patterson and Cotton Plant, with a peak flow reduction of about 10 percent.

River stages

Mean daily stages for the continuous gauges at Patterson, B5, James Ferry, and Cotton Plant are plotted for individual water years in Figure 13. The stages at the B8 gauge were not plotted as they were almost identical to the values recorded at the B5 gauge, with a different ground elevation. The discrete stage measurements on the surveyed transects are shown in Figure 14, and they exhibit a fair amount of variability compared to the roughly laterally constant water surface slope expected.

The time series of stage for Water Year 1990 (Figure 13c) shows that the floodplain can remain inundated throughout the two wet periods. The B5 gauge is about 300 m from the main channel on the right descending floodplain, and its stage stays about ground elevation from January into June. During the 1990 dry season, about seven rainfall events occurred. Two of these resulted in no overbank flows. The others resulted in minor inundation lasting from 1 to 3 weeks.

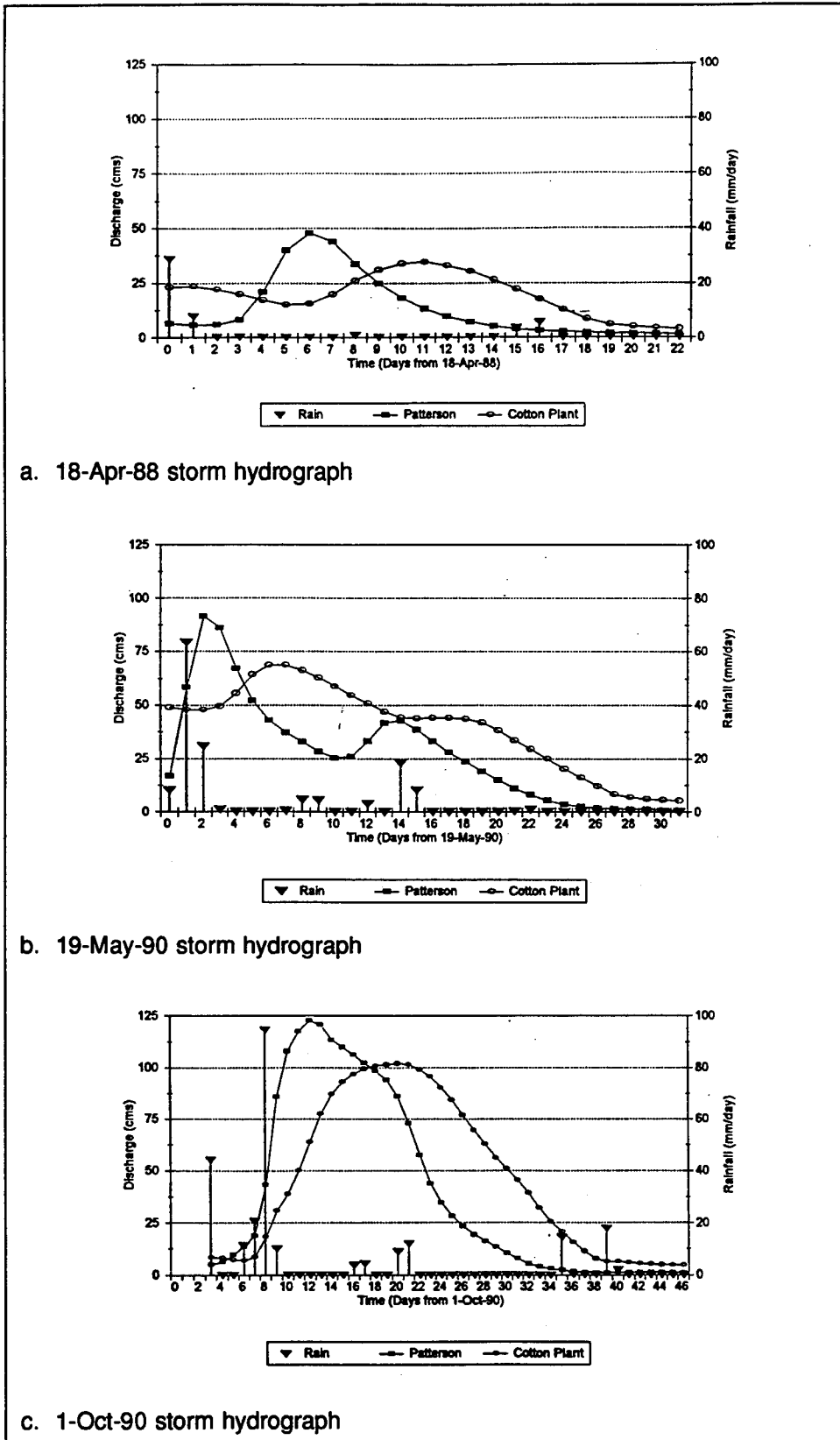


Figure 11. Plots of individual storm wind hydrograph with local average daily rainfall

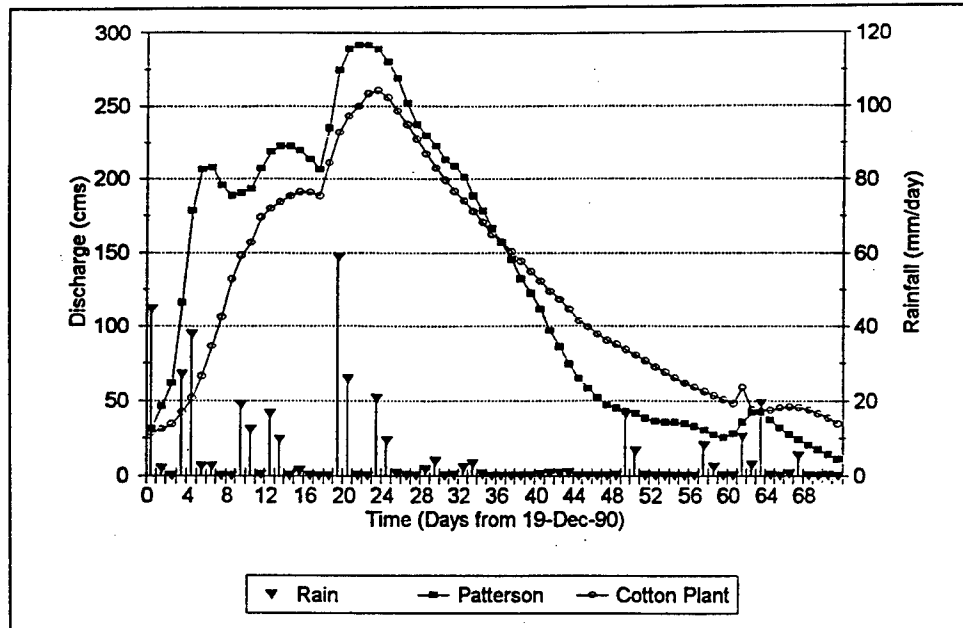


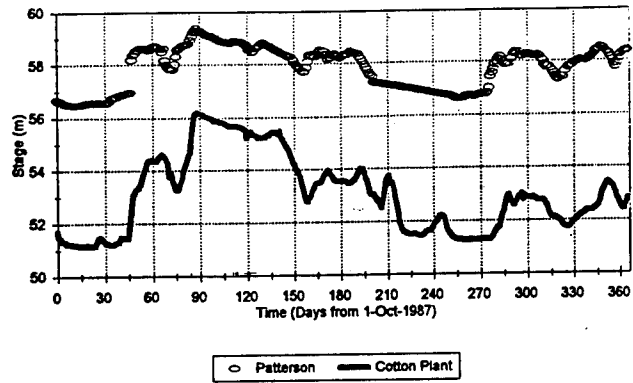
Figure 12. Winter hydrograph - Water Year 1991

Stage exceedance curves are plotted for each gauge in Figure 15. The median stages above NGVD were 58.1 m at Patterson, 55.2 m at B5, 54.3 m at James Ferry, and 53.0 m at Cotton Plant.

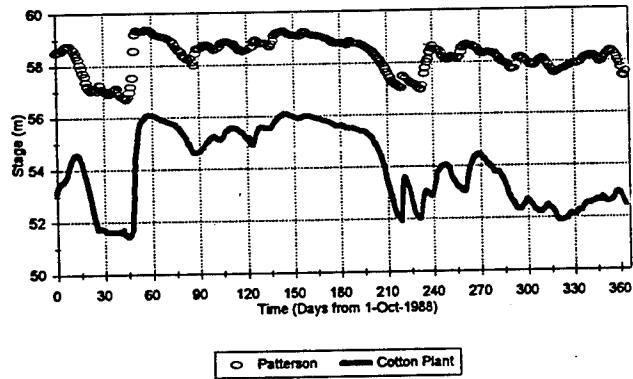
Data Analysis

Water balance

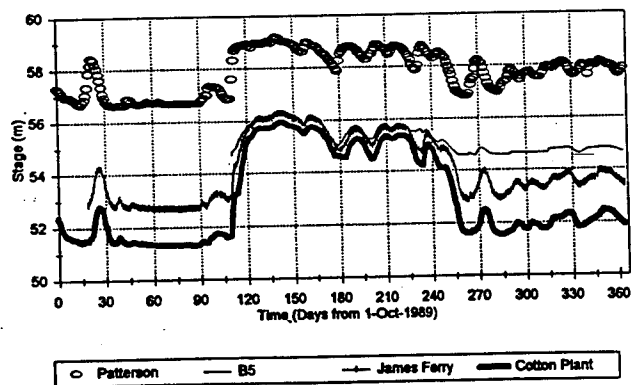
A water balance analysis provides a framework for assessing flow loss or gain within a wetland and to identify major system processes. A water balance for the Black Swamp was developed by examining rainfall, evapotranspiration (using the Priestley-Taylor (1972) method), infiltration, and river flows. Table 3 shows that river inflows and outflows dominate other sources and sinks of water. Nonstreamflow processes represent less than 10 percent of the long-term average river flows observed at Patterson and Cotton Plant.



a. Stages - Water Year 1988

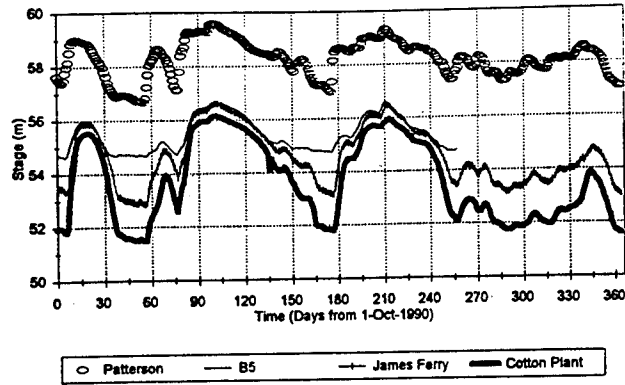


b. Stages - Water Year 1989

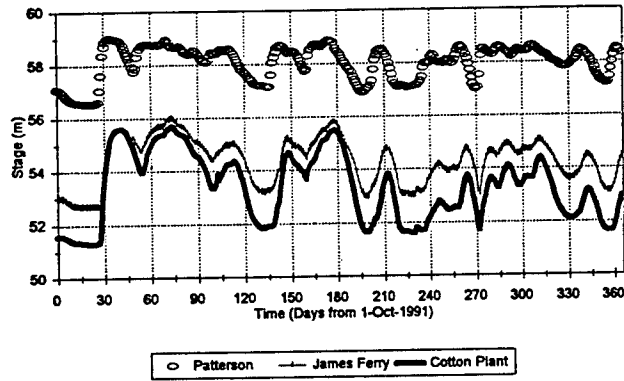


c. Stages - Water Year 1990

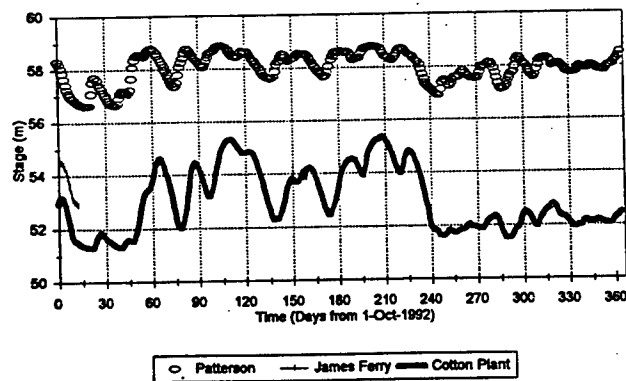
Figure 13. Mean daily stages for continuous gauge at Patterson, B5, James Ferry, and Cotton Plant (Continued)



d. Stages - Water Year 1991



e. Stages - Water Year 1992



f. Stages - Water Year 1993

Figure 13. (Concluded)

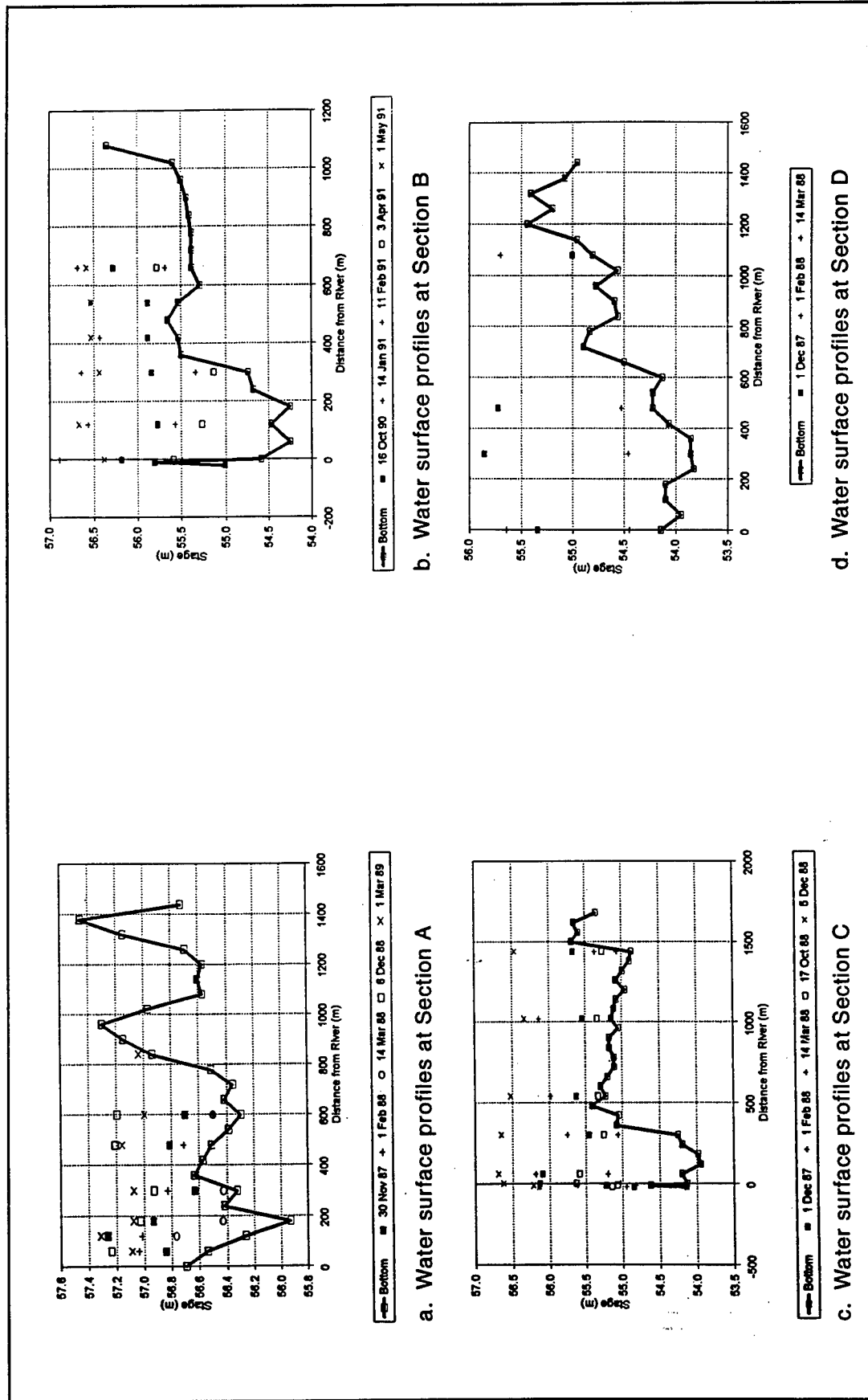


Figure 14. Discrete stage measurement on surveyed transects

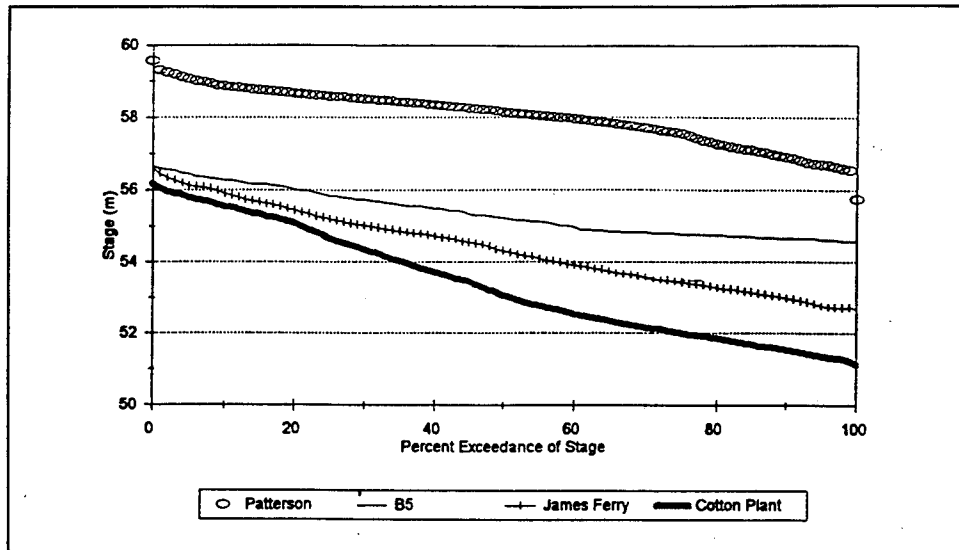


Figure 15. Stage duration—Patterson, Cotton Plant, B5, and James Ferry

Table 3 Annual Water Budget on the Black Swamp	
Variable	Annual Volume/Unit Area (m)
Inflow	14
Outflow	16
Rainfall	1
Evapotranspiration	1
Groundwater discharge	<1
Infiltration	<1

From Table 3, annual outflow minus annual inflow is approximately 2 m/unit area of wetlands. This value is consistent with the estimates for other H&H processes. However, well-gauged river flows are accurate to about 5-10 percent, and thus it is not possible to determine whether the differences between inflows and outflows are explained by other H&H processes, or by errors in the gauge values.

Major hydraulic and hydrologic processes

Peak flows are reduced between Patterson and Cotton Plant by an average of 10 to 20 percent, depending on the season (Figure 11). Inspection of the morphology of the watershed shows that flood flow alteration is dependent on the location and geometry of the wetland. The Cache River watershed shape is relatively long and narrow, and the Black Swamp is in the lower reach of the

river. The contribution of the wetland to streamflow at this location is small, generally less than 10 percent of upstream flows (Table 3). Flood peak attenuation depends mainly on inflow rates and duration.

Lateral spreading and overbank storage of the inflowing flood wave are responsible for much of the attenuation. This is particularly so when the system is initially dry and the event brief, as found during the dry season (Figure 11). When the system is initially wet or when the duration of the event is relatively long, as found during the wet season, the flood peak attenuation is smaller because overbank storage does not completely drain between storm events. Peak attenuation is caused most by aboveground, floodplain storage and to a lesser extent by overbank friction as the time base for the flood events is long compared to the time for the flood wave to travel laterally across the floodplain.

Perhaps the most important mechanisms causing overbank flooding in the Black Swamp are the constrictions near James Ferry and again at the Cotton Plant gauge. The effect of each constriction is to increase river stages upstream, and thus the surface water slope, sufficiently that the same flow can be forced through the smaller cross-sectional area of the constriction. From Figure 13, it can be clearly seen that as river flows increase, the water surface elevations at Cotton Plant, James Ferry, and B5 become more equal. The constrictions at James Ferry and Cotton Plant cause a backwater which is the primary mechanism causing overbank flow in the wetlands, where the river banks are low and floodplains extensive.

This process can be viewed another way by examining the water surface gradients. In Figure 16, the water surface gradient between James Ferry and Cotton Plant is compared to the stage at Cotton Plant. The figure shows that the water surface gradient decreases as the downstream stage increases.

Basin properties

The water balance analysis showed that river flows are the dominant H&H mechanism in the Black Swamp. However, the river flows are the result of upstream precipitation events in the Cache River watershed. Figure 17 compares the cumulative streamflow at Patterson and the rainfall falling on the Cache River watershed above Patterson. The results show that, on average, about one-third of the upstream rainfall becomes streamflow where rainfall was computed as gauge reading times the represented watershed area.

Hydroperiod

The length of time that an area is flooded is called the hydroperiod. The hydroperiod is of particular interest to wetland scientists who might relate this physical property to many different functions. In some cases, perhaps 50 years

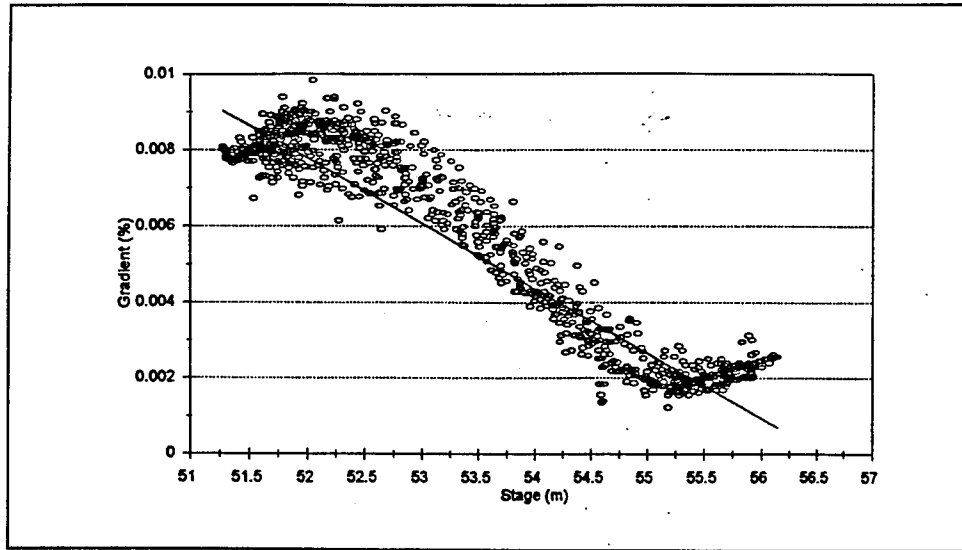


Figure 16. Cotton Plant stage and gradient between James Ferry and Cotton Plant

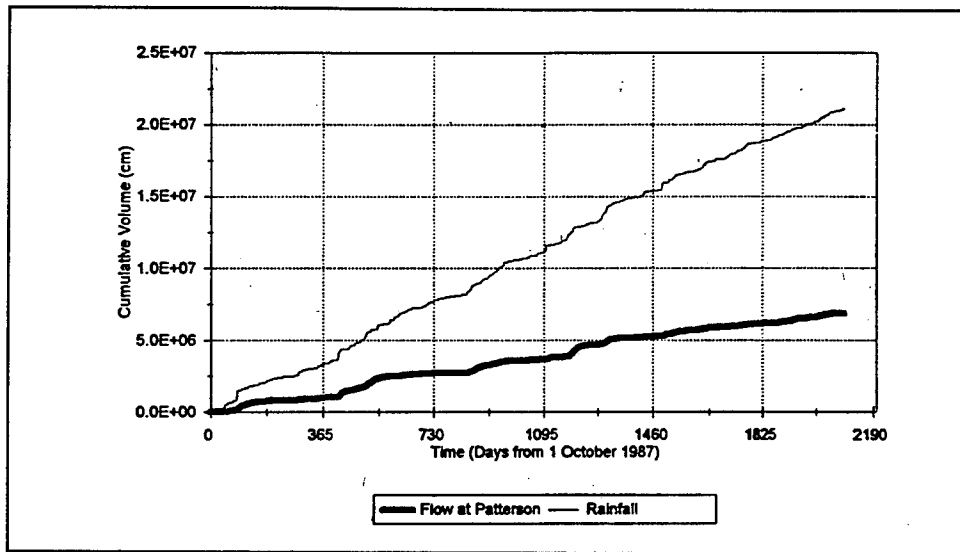


Figure 17. Cumulative flow and rain at Patterson

of hydroperiod information would be useful in evaluating some functions. Tree ring studies, for example, might use regression analyses based on stages at the Patterson gauge to estimate hydroperiods throughout the wetlands to correlate inundation with growth rates.

Regression analyses and scatter plots were made among the various gauges to determine relationships between stages, discharges, and depths of inundation. Figure 18 shows a scatter plot and regression analyses between discharges at Patterson and Cotton Plant. R^2 values were 0.810 for the linear regression and 0.817 for the log-log regression. Figure 19 shows scatter plots

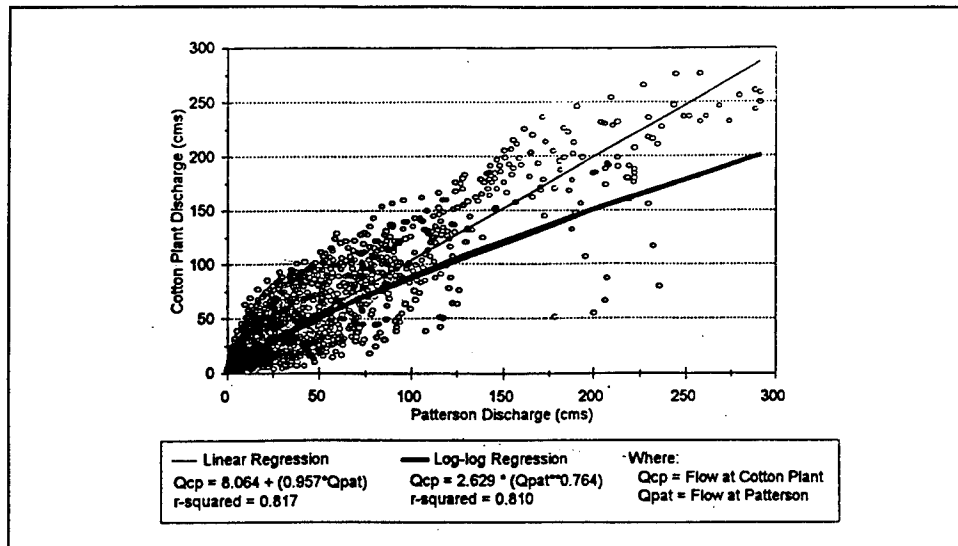


Figure 18. Regression analysis between flows at Patterson and Cotton Plant

of stages between Cotton Plant and the other upstream gauges. The results show a strong relationship between stages at Cotton Plant and James Ferry, a good relationship between Cotton Plant and B5, and only a fair relationship between Cotton Plant and Patterson. This suggests that the best predictor of overbank stages, such as at B5, would come from the stages at Cotton Plant.

The USGS gauge at Patterson, however, has the longest period of record of the gauges in the area. The record could be used to examine long-term inundation and hydroperiods in the wetlands. Figure 20 shows the linear regression between Patterson and B5 (representative of the main wetlands overbank area). The R^2 is 0.781 compared to an R^2 of 0.983 between Cotton Plant and B5. In an attempt to improve the correlation, the time lag for the flood wave to travel between Patterson and B5 and the bankfull elevations were also considered.

During the wet season, it was determined that Cotton Plant lags Patterson by about 4 days, on average. As B5 is about at the midpoint, a lag time of 2 days was selected for this analysis. From the observations of stage at Patterson and B5 (Figure 13), the stage at Patterson rises to about 57.5 m NGVD before overbank flooding is seen at B5, where the bank elevation is about 54.6 m NGVD. Therefore, the data were reanalyzed using 2-day-lagged stages at Patterson above 57.5 m and then compared to stages at B5 (Figure 21). The correlation improved to $R^2 = 0.888$. This is still not as well correlated as with the downstream gauge, but it does improve the relationship if assessments based on the long-term gauge record at Patterson are needed.

As the stages at Patterson and B5 are correlated, their hydroperiods should also be correlated. Using the original records of stage at the two gauges, the number of days that the stage at B5 exceeded each of 10 selected elevations were noted. The record at Patterson was then examined until 10 elevations

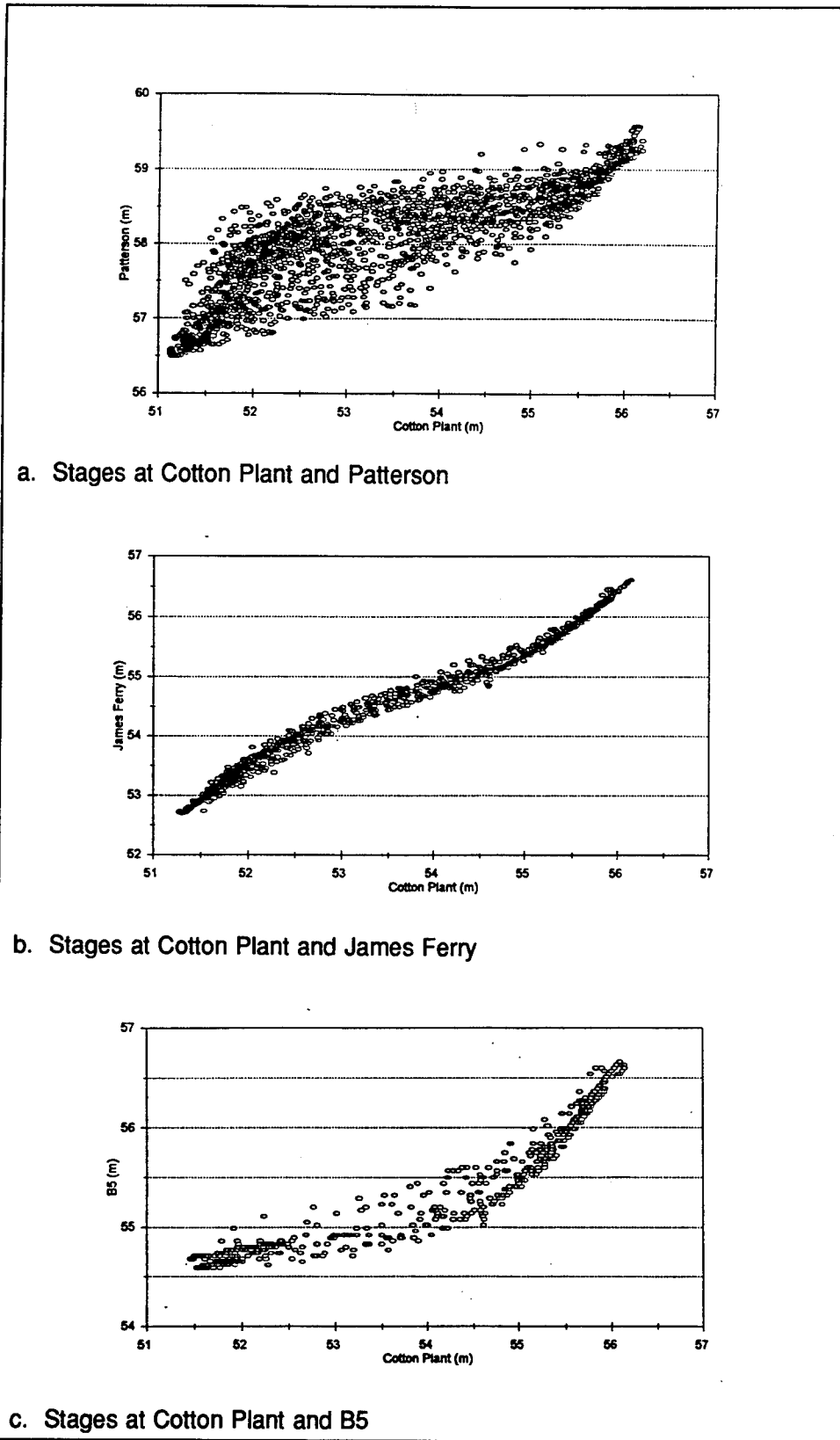


Figure 19. Scatter plots of stages between Cotton Plant and other upstream gauges

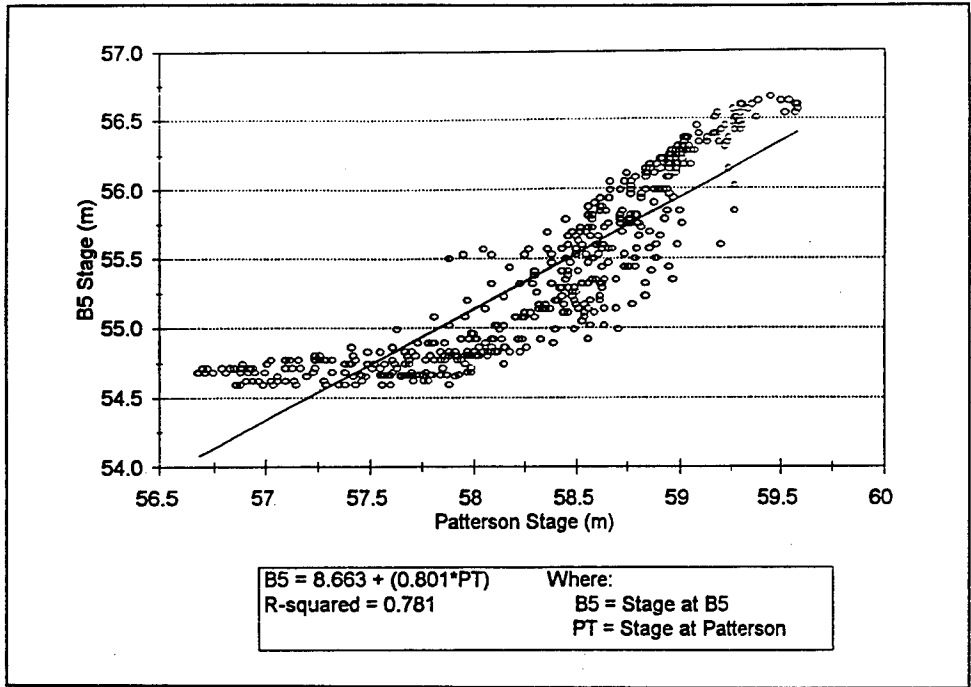


Figure 20. Regression analysis between stages at Patterson and B5 (no lag)

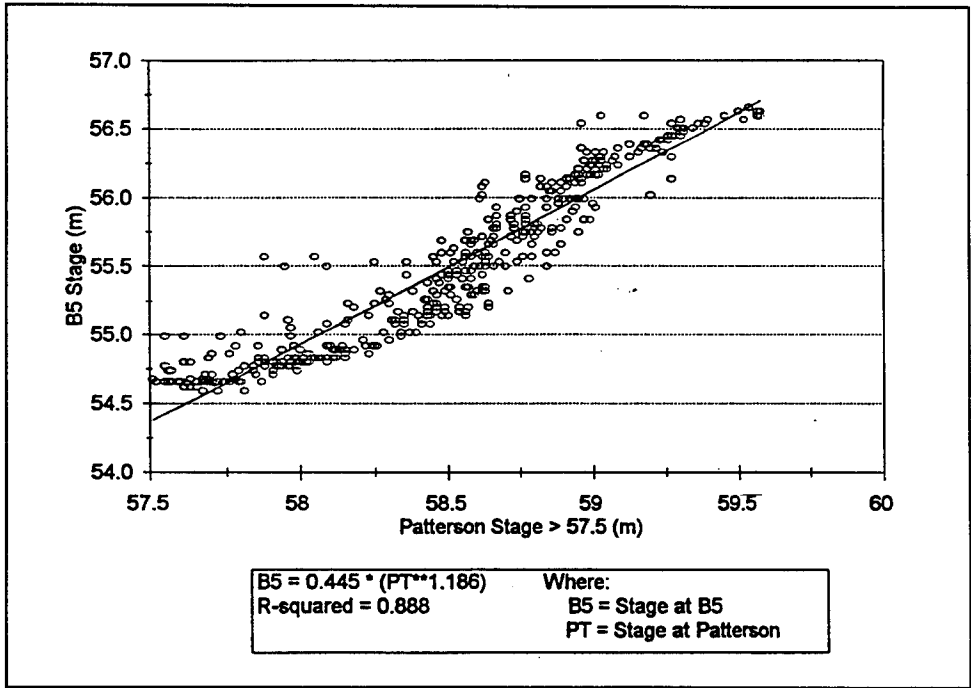


Figure 21. Regression analysis between stages at Patterson and B5 (2-day lag)

giving the same number of days of stage exceedance were determined. Mean hydroperiods for each gauge were then calculated by dividing the total number of days that the 10 elevations were exceeded by the number of “events” producing the exceedance. The results, shown in Table 4, indicate that a reasonable estimate of B5 hydroperiod can be made from observed stages at Patterson.

Table 4 Hydroperiod at Station B5 and Patterson					
B5			Patterson		
Elevation, m	Days	Mean	Elevation, m	Days	Mean
54.6	511	170	56.7	510	510
54.8	382	42	57.8	379	31
55.0	303	60	58.2	300	33
55.2	258	43	58.5	249	24
55.4	221	36	58.5	218	18
55.6	175	29	58.7	171	17
55.8	134	26	58.8	129	16
56.0	102	25	58.9	100	16
56.2	57	14	59.0	50	10
56.5	23	11	59.3	19	6

4 Model Development

In Chapter 2, the major H&H processes and data resources for various types of wetlands were identified and discussed. These processes and their role in the hydrologic cycle are shown in Figure 22. Their numerical description is the basis for the development of the Wetlands Dynamic Water Budget Model discussed in this chapter.

One requirement of the Wetlands Dynamic Water Budget Model is the ability to simulate the long-term response of a wetland to hydrologic forcing. This suggests emphasizing efficiency and reducing grid resolution and dimensionality to perform long simulations in a reasonable amount of time. The model includes three major modules—surface water, vertical processes, and horizontal groundwater flow (Figure 23) which are internally linked. The development of the individual modules is described below.

Spatial and Temporal Resolution

Various modeling approaches and methodologies were reviewed (Walton and Chapman 1991), and it was decided to base the model development on the link-node approach. An application of a link-node model (Hales et al. 1990) to the Bolsa Chica wetland, and other applications, showed that the link-node scheme is conceptually simple, flexible, easy to use, and gives accurate results. In addition, it can be readily configured to look like a finite-difference scheme, or a “block-centered” scheme, such as in the groundwater flow model, MODFLOW (McDonald and Harbaugh 1988). It is a simple example of a “finite-volume” scheme.

The link-node method (Figure 24) divides the system into a series of finite volumes called “nodes” or “junctions” where stage is defined. Flows are defined along one-dimensional (1-D) channels called “links” between adjacent nodes. The scheme is flexible because it can easily represent complex geometry; it is simple to program and use because the links are 1-D equations of flow, which are efficient to solve numerically. Finally, its structure readily permits the linkage of horizontal and vertical processes between the surface water and the groundwater.

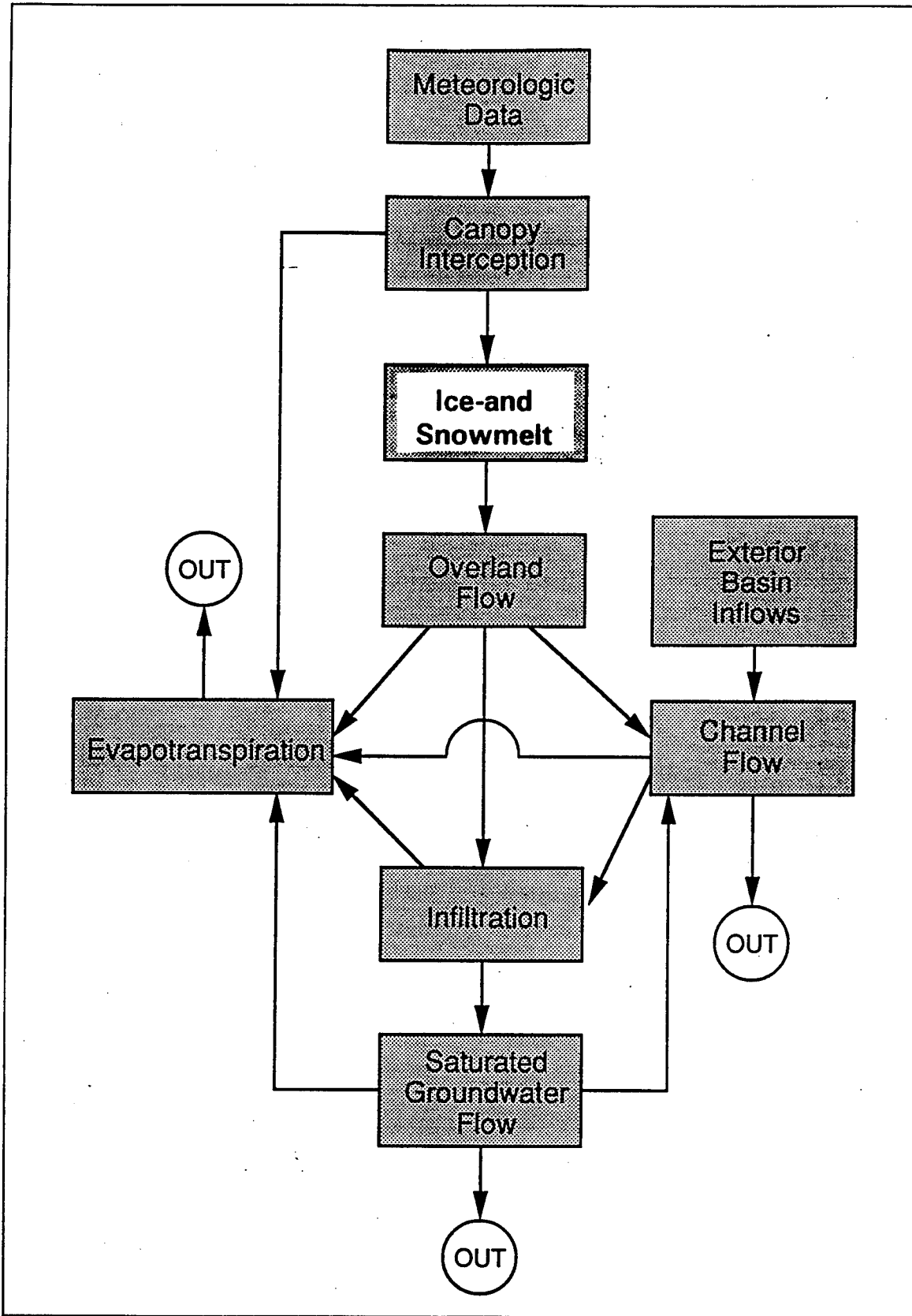


Figure 22. Schematic processes

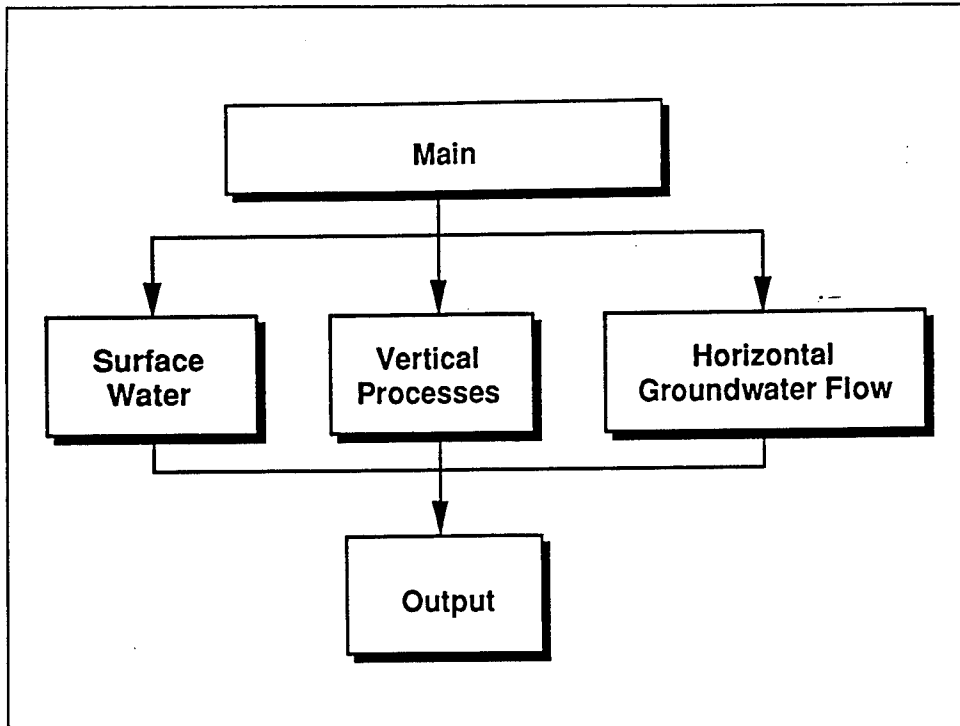


Figure 23. Three modules of Wetlands Dynamic Water Budget Model

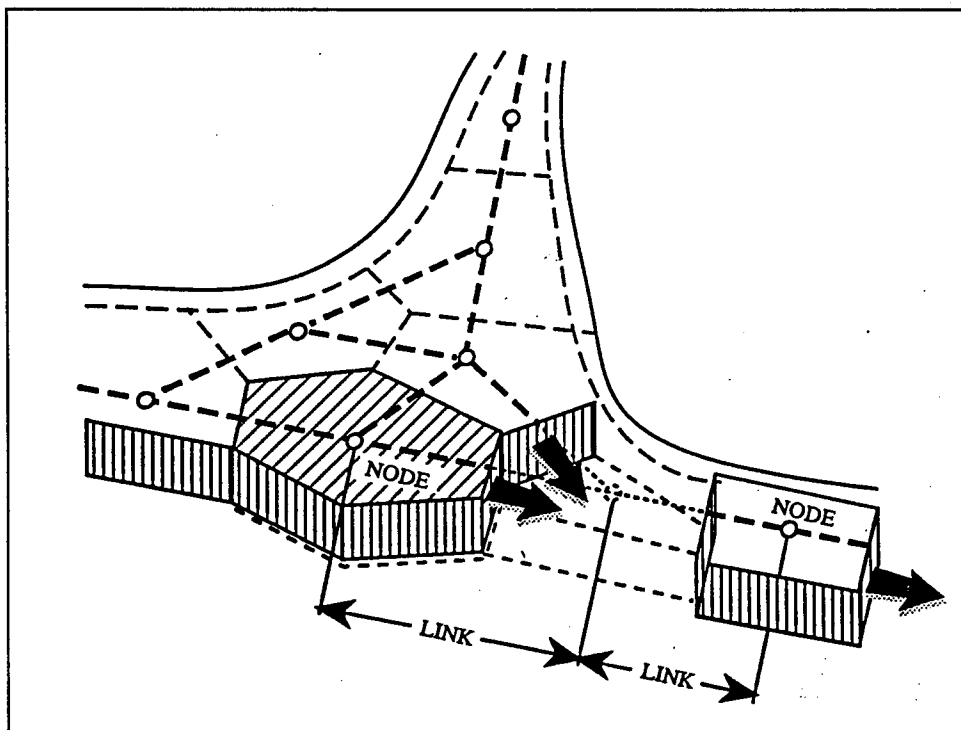


Figure 24. Link-node schematic

The model developed uses explicit time-stepping, and each of the three modules uses the same time interval Δt .

Surface Water Module

Processes simulated

The surface water module was designed to simulate the following processes:

- Channel and overbank flows
- Tidal forcing
- Riverine inflows and upstream basin flows
- Wind shear
- Flooding and drying
- Various bottom friction types
- Hydraulic structures (culverts, weirs, and gates)

Theory and solution technique

The surface water module of the Wetlands Dynamic Water Budget Model is based on the Dynamic Estuary Model (DEM), which is a link-node model successfully applied to the Bolsa Chica wetland in California (Hales et al. 1990, Walton et al. 1989). A very similar link-node hydrodynamic model, DYNHYD5, is a subprogram for the Environmental Protection Agency (EPA) water quality model WASP4 (Ambrose et al. 1988).

In general, link-node models solve 1-D equations describing the propagation of a long wave through shallow water by conserving momentum in links and mass or volume at nodes (Figure 24). The approach has three assumptions: (a) the flow is predominantly unidirectional along each link; (b) Coriolis and other accelerations normal to the direction of flow are negligible, and (c) individual links have uniform cross-sectional areas. The resulting system is highly flexible because complex geometries of interlinked waterways and overbank areas can be easily represented, and the 1-D nature of the governing equations allows for efficient solution for long-term simulations with generally minimal errors.

The equations for conservation of momentum and volume are written:

$$\frac{\partial Q}{\partial t} + \frac{\partial(\beta Q^2/A)}{\partial x} + gA \frac{\partial y}{\partial x} = gA (S_0 - S_f) \quad (2)$$

and

$$\frac{\partial V}{\partial t} = \sum_{n=1}^N Q_n + Q_i \quad (3)$$

where

Q = flow rate

β = momentum correction factor

A = cross-sectional area of link

g = acceleration due to gravity

y = water depth

S_0 = bed slope

S_f = friction slope

V = nodal volume

Q_n = flow rate in link "n"

N = number of channels (links) entering a node

t = time

x = longitudinal distance along link

Q_i = other inflows, such as precipitation, basin inflows, etc.

The version of the link-node model used for the surface water module has been modified to permit a variety of link types that depend on which terms within the momentum equation are included. If all the terms are included, the equation is called the "dynamic wave" equation, which is usually used to simulate channel flow. If the acceleration terms are neglected, the equation is called the "diffusion wave" equation:

$$\frac{\partial y}{\partial x} = S_0 - S_f \quad (4)$$

This form is often used to simulate overbank flow.

Most of the overland routing models formulate friction in terms of either Manning's n or Chezy's C coefficients. This assumes that the flow is in the rough turbulent range. In practice, however, as pointed out by Kadlec (1990), a different power law formulation may give results in better agreement with observations. Thus, in the wetlands model, a variable formulation is used:

$$S_f = \frac{Cu^{p_1}}{R^{p_2}} \quad (5)$$

where

R = hydraulic radius

u = longitudinal velocity

C = friction coefficient

p_1, p_2 = powers

If, for example, $C = n^2$, $p_1 = 2$, $p_2 = 4/3$, Manning's equation is obtained,

where n = Manning's friction coefficient

Wind shears are modeled using Large and Pond (1981):

$$F_w = 1.2 \times (10^{-6}) w_s^2 \text{ for } w_s < 11 \text{ m/s} \quad (6)$$

$$F_w = (0.49 + 0.065 w_s) \times (10^{-6}) w_s^2 \text{ for } w_s > 11 \text{ m/s}$$

where

F_w = wind shear function (m^2/sec^2)

w_s = wind speed at a 10-meter elevation (m/sec)

The wind direction is specified in the meteorologic convention as "from which the wind blows," and converted in the model to the oceanographic convention as "toward which the wind blows."

Hydraulic structures

One feature of the link-node formulation is that it is easy to represent hydraulic structures, such as culverts, weirs, and gates, by replacing the momentum equation in that link with the appropriate hydraulic structure equation.

Culverts are simulated using Equation 2, without the nonlinear terms and with the cross-sectional area A describing the flow area within the culvert. The model checks for critical flow within the culvert to set the appropriate flow area. Experience on the Bolsa Chica study (Hales et al. 1990) showed that inlet and outlet losses are not important when describing regional flow, and so they are neglected. Finally, the culvert length is adjusted (lengthened) so that the governing momentum equation remains stable. To compensate, Manning's friction factor is adjusted:

$$n_{eq} = n(L/L_{eq})^{1/2} \quad (7)$$

where

n_{eq} = adjusted (equivalent) Manning's friction factor

n = specified Manning's friction factor

L = length of culvert

L_{eq} = adjusted (equivalent) length of culvert

so that the momentum equation retains the correct effect.

Broad crested weirs are simulated using (Henderson 1966):

$$Q = 0.54 g^{1/2} C B^{3/2} \quad (8)$$

where

Q = flowrate

g = acceleration due to gravity

C = dimensionless weir coefficient of discharge

B = weir length

d = water depth over weir

When the weir is drowned (defined in the model as the point at which the downstream depth exceeds the weir crest elevation), the model switches to Equation 2.

Gates are simulated using (Henderson 1966):

$$Q = C_d A (2g\Delta H)^{1/2} \quad (9a)$$

$$C_d = \left[\frac{C_c}{1 + C_c W/y_1} \right] \quad (9b)$$

where

Q = flowrate

C_d = gate coefficient of discharge

A = cross-sectional area

g = acceleration due to gravity

ΔH = head difference across gate

C_c = gate contraction coefficient

W = gate opening

y_1 = upstream depth

Boundary conditions

The model allows several types of boundary conditions:

- a. Stage hydrograph.
- b. Flow hydrograph.
- c. Loop rating curve.
- d. Specified rating curve.
- e. Inflows from upstream basins.

The stage hydrograph, often used as a downstream boundary condition where a gauge is available, prescribes the stage through time as:

$$H = H(t) \quad (10)$$

where

H = stage

$H(t)$ = specified values over time

In the Wetlands Dynamic Water Budget Model, values are read from a file at user specified times and are interpolated to the current model time.

The flow hydrograph, often used as an upstream boundary conditions where a gauge is available, prescribes the flow through time as:

$$Q = Q(t) \quad (11)$$

where

Q = flow

$Q(t)$ = specified values over time

In the Wetlands Dynamic Water Budget Model, stage and discharge values are read from a file at user specified times and are interpolated to the current model time.

Often, there are no downstream boundary data available, either to use directly or from which to develop a stage-discharge rating curve. In these cases, it is often possible to use a "loop" rating curve. The model solves an additional equation for flow and uses it as an outflow from the system to calculate the new downstream stage. For relatively steep slopes (greater than 1 percent), a Manning friction-based diffusion wave equation is used:

$$Q = \frac{1}{n} A R^{2/3} \left(\frac{\partial H}{\partial x} \right)^{1/2} \quad (12)$$

where

R = hydraulic radius

x = longitudinal distance

For milder slopes (less than 1 percent), Manning's equation is used:

$$Q = \frac{1}{n} A R^{2/3} S_0^{1/2} \quad (13)$$

where S_0 = bottom slope

Equation 12 will produce a “loop” rating curve, where a given flow will produce two different values of stage depending on whether the flood event is rising or falling. However, for mild slopes (usually less than 0.5 percent, but sometimes less than 1 percent), the difference between the two heads is small, and the method can produce unstable results.¹ Using Equation 13 for mild slopes overcomes this problem and yields the single valued rating curve usually seen under these conditions.

Occasionally, when there are adequate data to describe the downstream boundary, but the model is being run for a period not described by the observations, it is appropriate to use a prescribed stage-discharge rating curve. There are a number of ways this condition could be implemented including a “look-up” table or a power series. The Wetlands Dynamic Water Budget Model uses a power series of the form:

$$Q = a_0 + a_1 y + a_2 y^2 + a_3 y^3 + a_4 y^4 \quad (14)$$

where

a_0 - a_4 = coefficients determined by curve-fitting analysis

y = water depth at a boundary node

Finally, flow from an upstream, perhaps ungauged basin, can be introduced to the model using the “Rational Formula”:

$$Q_b = C i A_b \quad (15)$$

where

Q_b = basin inflow

C = coefficient in range 0 to 1

i = precipitation rate

A_b = basin area

Common values of the runoff coefficient C can be found in standard reference handbooks, such as Chow (1964).

¹ Danny Fread. (1993). National Weather Service, personal communication.

Vertical Processes Module

The processes simulated in the vertical direction are:

- Canopy interception
- Surface water evaporation
- Soil water evaporation
- Transpiration
- Infiltration

The vertical direction is divided into a number of soil layers (Figure 25), which correspond to the layers in the groundwater model. Above the soil layers are the surface water and canopy layers. Much of the theoretical description of the processes simulated in the Wetlands Dynamic Water Budget Model comes from two sources—the HELP model (Schroeder et al. 1988) and the SHE model (Abbott et al. 1986, DHI 1991).

Incident radiation and potential evapotranspiration

The HELP model (Schroeder et al. 1988) and a predecessor, the SPUR model (Wight and Skiles 1987), define the fraction of the net radiation striking the canopy as:

$$f_c = 1 - e^{-k_n LAI} \quad (16)$$

where

f_c = fraction of radiation striking canopy

k_n = coefficient (=0.4 in HELP and SPUR models)

LAI = leaf area index (m^2 of leaf area/ m^2 of ground)

In their work, for nontreed sites, they then define the fraction available for surface water and soil water evaporation as $LAI/3$ (for $LAI < 3$). However, for many treed sites during the growing season, the LAI will be larger than 3, and there is the possibility that the fraction of the net radiation summed over the canopied and noncanopied areas will be greater than 1. If aerodynamic resistance is neglected, then of the total net radiation R_n , the canopy can use the fraction f_c for canopy evaporation and root transpiration. The remainder $1-f_c$ is used in areas without canopies for surface water and soil water evaporation.

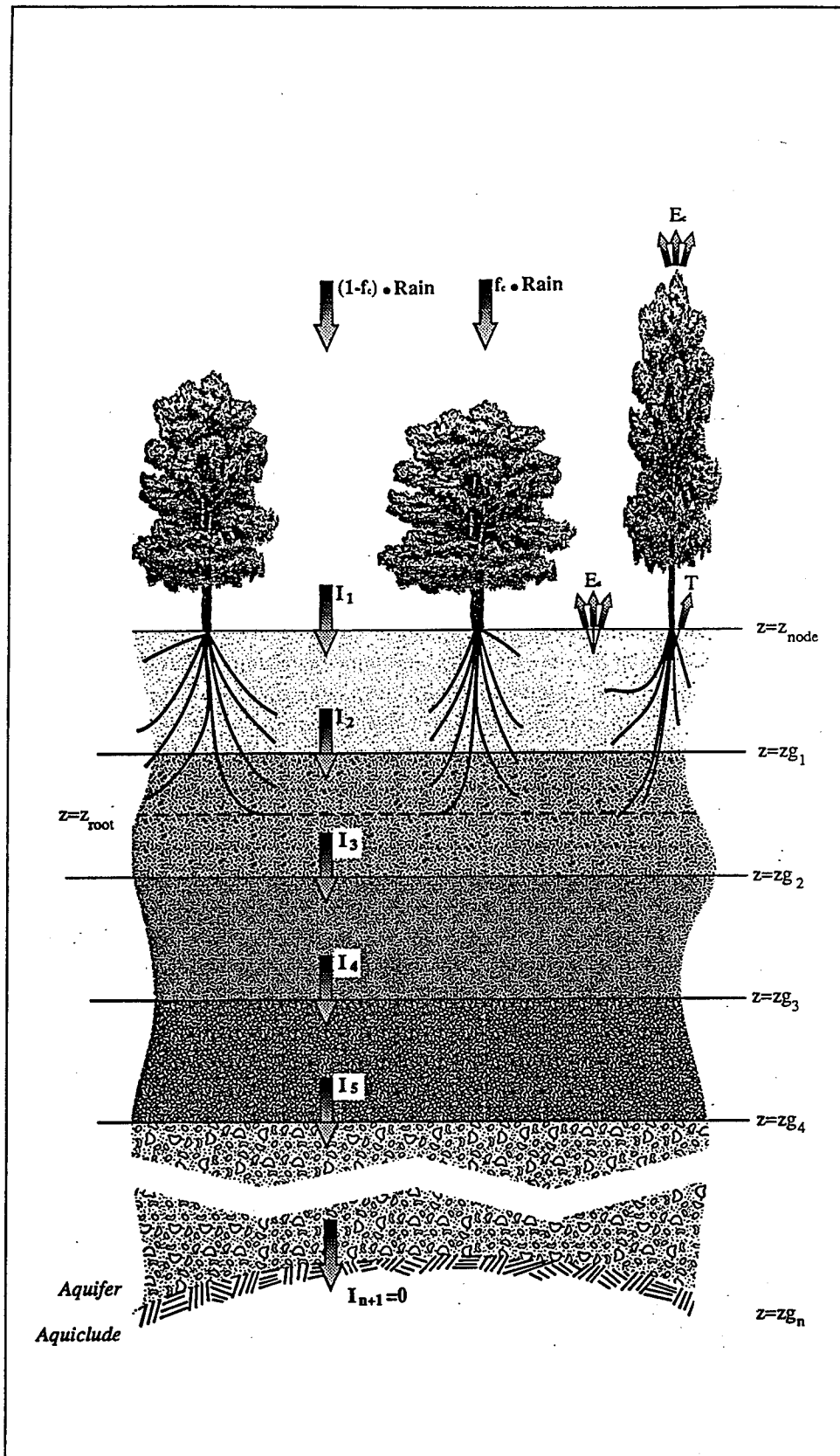


Figure 25. Vertical flow processes

The Wetlands Dynamic Water Budget Model uses the Priestley-Taylor (1972) form of Penman's combination equation used in the HELP model (Schroeder et al. 1988):

$$ET_p = 1.28 A \frac{H}{A+G} \quad (17)$$

where

ET_p = potential evapotranspiration (mm/days)

A = slope of saturated vapor pressure curve

H = net solar radiation (Langley/day)

G = psychometric constant (= 0.68)

Some of the parameters can be estimated using (Schroeder et al. 1988):

$$A = \frac{5304}{T_k^2} e^{21.255-5304/T_k} \quad (18)$$

where T_k = air temperature in degrees kelvin

$$H = (1-L) \frac{R_s}{58.3} \quad (19)$$

where

L = albedo for solar radiation (assumed = 0.3)

R_s = total incoming solar radiation (Langley/day)

Canopy Interception, drainage, and evaporation

Of the rainfall (R) falling on each computational cell, the fraction $f_c R$ strikes the canopy. Rutter, Morton, and Robbins (1975) used a simple mass balance in the canopy:

$$\frac{\partial C}{\partial t} = R - D \quad (20)$$

where

C = depth of water on canopy

R = rainfall rate

D = drainage from the canopy

In the Rutter model, the drainage D is defined by:

$$\begin{aligned} D &= 0 && \text{for } C < S \\ D &= D_s e^{b(C-S)} && \text{for } C > S \end{aligned} \quad (21)$$

where

D_s = drainage rate at $C = S$

b = drainage coefficient

S = depth on canopy when drainage starts

The drainage from the canopy and the rain directly falling on the ground not covered by the canopy are then used to define the rate of change of volume of surface water in a cell:

$$\frac{\partial V}{\partial t} = f_c D A_s + (1 - f_c) R A_s \quad (22)$$

where

V = volume of surface water in cell

A_s = surface area of cell

Finally, evaporation from the canopy E_c is defined as:

$$E_c = \min (ET_p, C) \quad (23)$$

and the remaining potential for transpiration T_p is:

$$T_p = ET_p - E_c \quad (24)$$

Surface water evaporation

If there is surface water in the cell, either from canopy drainage, direct rainfall, or overbank flooding, the surface water evaporation E_{sw} is defined as:

$$E_{sw} = \min \left(ET_p, \frac{y}{\Delta t} \right) \quad (25)$$

where

y = depth of water on ground = V/A_s , and

Δt = time-step in model

The remaining potential for soil water evaporation ES_p is:

$$ES_p = ET_p - E_{sw} \quad (26)$$

Soil water evaporation

The approach to soil water evaporation is the same as that in the HELP (Schroeder et al. 1988) and SPUR (Wight and Skiles 1987) models. In this approach, soil evaporation depends on the energy available at the ground surface and the soil water content in the upper model layer.

Soil water evaporation is divided into two stages. In stage 1, evaporation is controlled by the available energy at the surface. In stage 2, evaporation is controlled by the rate that water can be transmitted through the soil. The upper limit of stage 1 soil evaporation U is defined (in SI units) by:

$$U = 9 (CON - 3)^{0.42} \quad (27)$$

where CON = evaporation coefficient

Stage 1 soil evaporation E_{s1} is defined as:

$$E_{s1} = ES_p = ET_p - E_{sw} \quad (28)$$

and occurs when:

$$\sum (E_{s1} + T_d - I) < U \quad (29)$$

where

T_d = transpiration from upper soil layer

I = net infiltration into upper soil layer

Stage 2 soil evaporation E_{s2} occurs when the total soil water lost exceeds the upper limit U and is given by:

$$E_{s2} = CON (t^{1/2} - (t-1)^{1/2}) \quad (30)$$

where t = days since stage 2 soil evaporation began

Transpiration

Of the net radiation striking the canopy, the potential remaining after canopy water evaporation T_p is available for transpiration. Transpiration occurs within the root zone of the overlying canopy. In the Wetlands Dynamic Water Budget Model, it is assumed that the local potential linearly decreases to zero at the root zone depth:

$$T_p(z) = 2T_p \left(\frac{1 - \frac{z}{z_r}}{z_r} \right) \quad (31)$$

where

$T_p(z)$ = transpiration potential at depth z

z_r = depth of root zone from surface

This equation is converted to a series of layer weights by integrating over individual layer thicknesses.

Available soil water also controls transpiration. Generally, transpiration does not occur below the wilting point of the vegetation and can occur at the potential rate above the field capacity.

The Wetlands Dynamic Water Budget Model uses the form applied in the SPUR model (Wight and Skiles 1987):

$$T_d = T_p \frac{\theta}{0.25 \theta_{fc}} \quad (32)$$

where

T_d = transpiration demand

θ = soil water content

θ_{fc} = field capacity

Infiltration

Infiltration is modeled using Darcy's equation. The theoretical description is identical to that for horizontal groundwater flow described in the next section, except that ks_v , the vertical saturated hydraulic conductivity, replaces the horizontal saturated hydraulic conductivity ks_h .

Horizontal Groundwater Flow Module

The horizontal groundwater flow module simulates variably saturated horizontal flow in the same layers as defined for the vertical processes module. Processes included are:

- Variably saturated horizontal groundwater flow
- Fixed-head boundary conditions
- Wells

Theory and solution

The subsurface region is divided into a number of layers sufficient to describe vertical variations in soil properties, or to provide sufficient resolution of vertical processes (Figure 26). In each vertical layer, the horizontal discretization of the soil is the same as used in the surface water module.

Horizontal groundwater flow, both in the unsaturated and saturated zones, is based on Darcy's Law:

$$Q_g = k_h A \frac{\partial H}{\partial x} \quad (33)$$

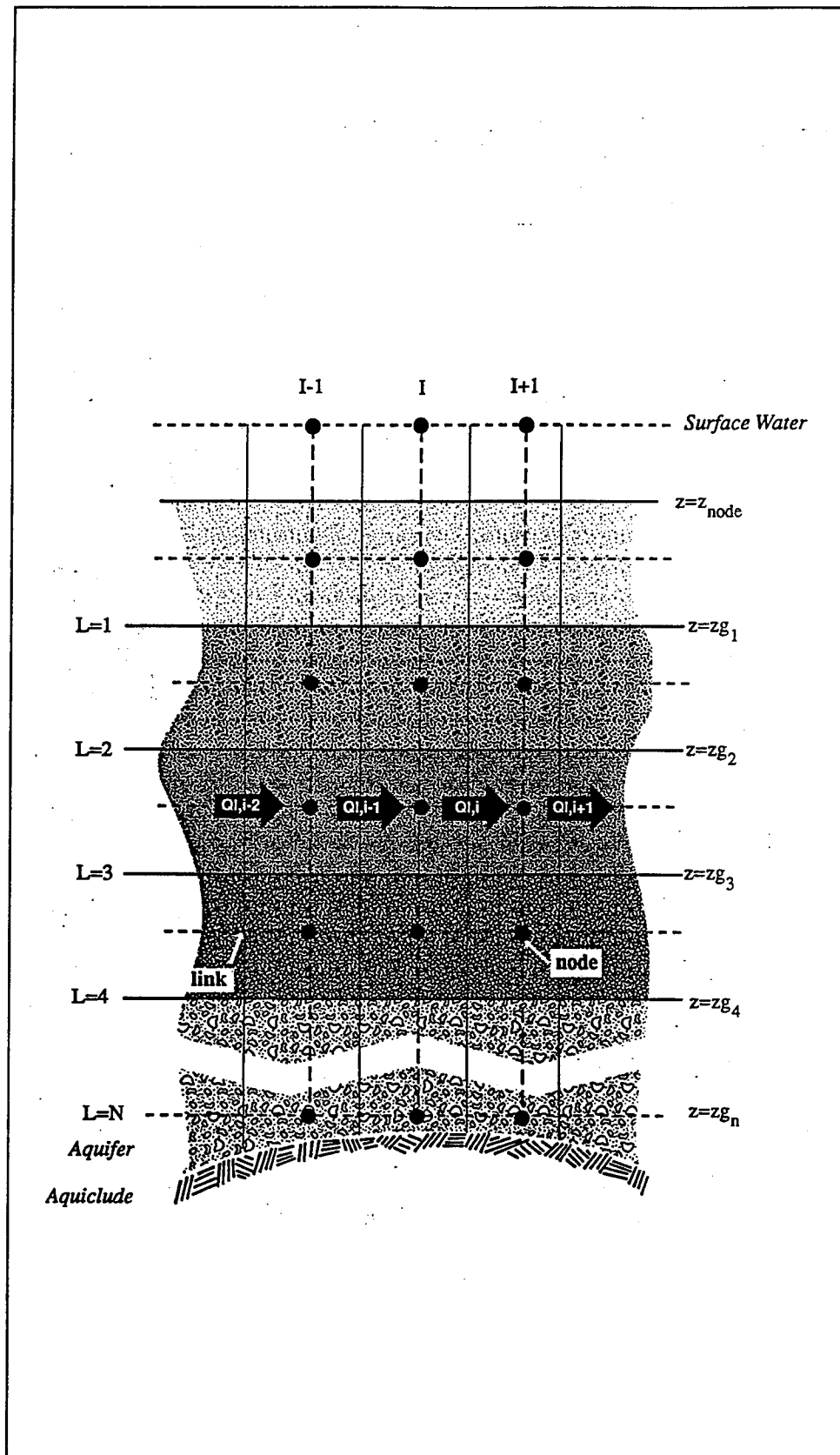


Figure 26. Horizontal groundwater flow

where

Q_g = horizontal flow in link

k_h = horizontal hydraulic conductivity

A = cross-sectional area of link

H = piezometric head above datum

x = longitudinal distance

Defining the total (potentiometric) head H as:

$$H = z - \psi \quad (34)$$

where

z = elevation above datum

ψ = soil moisture tension

and the relationship between soil moisture tension ψ and soil moisture θ as (Brooks and Corey 1966):

$$\theta^* = \frac{\theta - \theta_r}{\phi - \theta_r} = \left(\frac{\psi^*}{\psi} \right)^\lambda \quad (35)$$

where

θ^* = normalized soil moisture content

θ = soil moisture content

θ_r = residual soil moisture content

ϕ = saturated soil moisture content

ψ^* = air suction (air-entry) head

λ = pore-size distribution index

then the form of the horizontal hydraulic conductivity k_h is given by (Brooks and Corey 1966):

$$\begin{aligned}
 k_h &= ks_h && \text{for } \psi < \psi^* \\
 k_h &= ks_h \left(\frac{\psi^*}{\psi} \right)^{2+3/\lambda} && \text{for } \psi > \psi^*
 \end{aligned}
 \tag{36}$$

where ks_h = saturated horizontal hydraulic conductivity

This form for the unsaturated hydraulic conductivity is used in the HELP model and is one of the options in the three-dimensional (3-D) variably saturated groundwater flow model, PORFLO-3 (Sagar and Runchal 1990).

Once the flow has been computed from Equation 33, and the vertical flow is computed (using the same approach), the total (potentiometric) head H at each subsurface node is calculated from the continuity equation:

$$S_s A_s \frac{\partial H}{\partial t} = \sum_{n=1}^N Q_n + Q_s
 \tag{37}$$

where

S_s = specific storativity

A_s = surface area of node

n = link number entering node

N = number of links entering a node

Q_n = flow in link n

Q_s = source/sink flows to node

Using soil properties defined in the HELP model documentation (Schroeder et al. 1988), Figures 27 and 28 show the relationships between normalized soil moisture content and soil moisture tension (using Equation 35) and between normalized soil moisture content and hydraulic conductivity (Equation 36), respectively, for a range of soil types. These figures illustrate the forms of these equations and permit insight into the nonlinearities of the processes being modeled.

Boundary conditions

The model allows the specification of fixed-head boundary conditions. No flow boundaries are treated automatically by not prescribing an exterior flux at a boundary node. Specified flux boundary conditions can be treated using

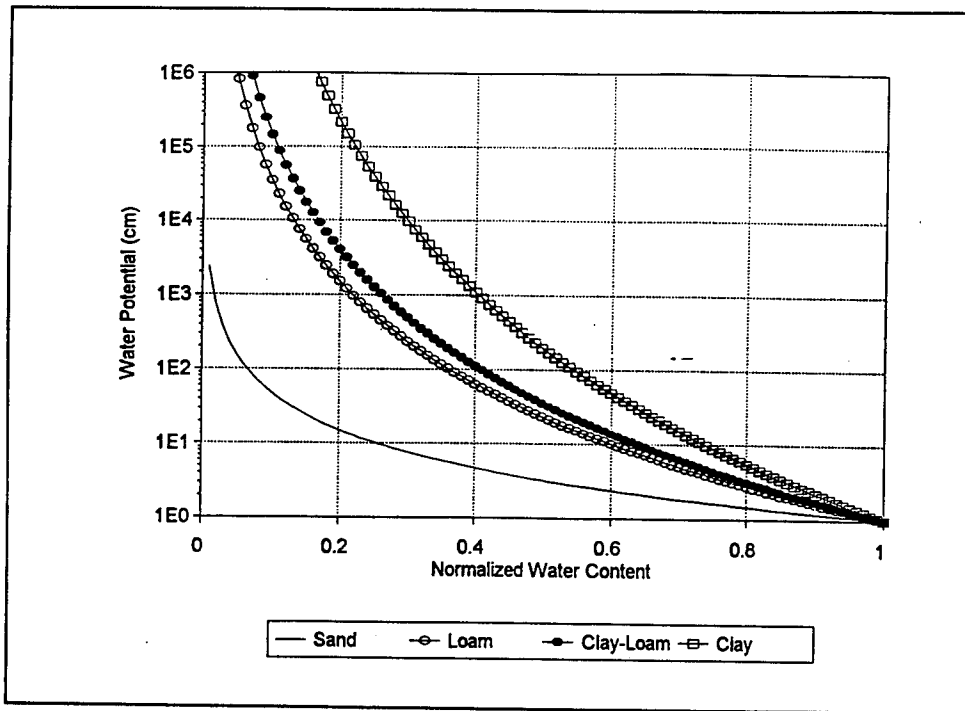


Figure 27. Soil retention curves

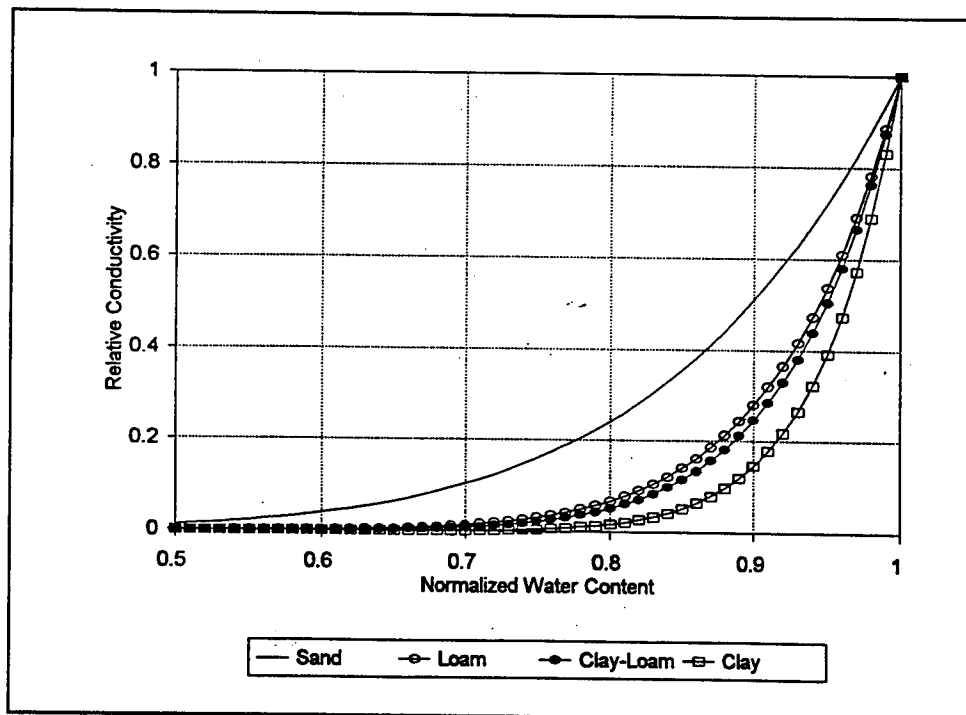


Figure 28. Relative conductivity for various soil types

“wells.” Wells are simulated by applying an exterior flux to a specified node in a specified layer. Negative values of flux represent withdrawals, and positive values represent recharge wells.

Model Linkage

The three modules are linked in two ways. The surface water module is linked to the vertical processes module through the surface water volume at each node. The vertical processes module is linked to the horizontal groundwater flow module through the soil moisture content of each cell (node/layer pair). The surface water module needs no direct linkage to the groundwater flow module as they both represent horizontal processes.

Stability Conditions

The model is governed by two stability conditions. As the channel flow routine of the surface water module is based on an explicit link-node scheme, it is governed by the Courant condition in each link:

$$\Delta t \leq \frac{\Delta x}{\sqrt{gy}} \quad (38)$$

where

Δt = the model time-step

Δx = the length of a link

g = acceleration due to gravity

y = flow depth

Flow in the vertical and groundwater modules is also treated explicitly, using the same time-step as for the surface water module. The time-step is governed by the condition in each link:

$$\Delta t \leq \frac{S_s \Delta s}{2k_s} \quad (39)$$

where

S_s = specific storativity

Δs = link distance (horizontal or vertical)

k_s = saturated hydraulic conductivity (horizontal or vertical)

It can be readily seen from Equation 39 that the vertical form of this condition will generally be more severe than the horizontal. Usually, the vertical saturated hydraulic conductivity is an order of magnitude smaller than the horizontal. However, the vertical resolution, Δs , might be several orders of magnitude smaller than the horizontal.

5 Model Testing

The sections below discuss the testing of the three major modules of the Wetlands Dynamic Water Budget Model—surface water, vertical processes, and horizontal groundwater flow.

Surface Water Flows

The surface water module was intended to simulate flows and elevations in both riverine and tidal wetlands; therefore, several cases that would test these capabilities were identified.

Test 1 simulated “normal” flow in a wide rectangular channel. A 10-km channel, modeled using 11 nodes and 10 links (each 1 km long), with a bottom slope of $S_0 = 1\text{m/km}$ was specified. The width of the channel was 100 m, and a flow of $100\text{ m}^3/\text{sec}$ specified at the upstream end. Using a uniform Manning’s friction coefficient of $n = 0.04$, the theoretical normal depth is 1.15 m. The model was run specifying a (a) fixed depth of 1.15 m at the downstream boundary and (b) loop rating curve based on Manning’s equation at the downstream boundary. From initial starting depths of 2 m, the model simulated the normal depth of 1.15 m throughout the channel length in each case.

Test 2 simulated tidal flows in a closed-end channel and is described in detail in Wang and Conner (1975). A channel with a length of 200 m, a width of 100 m, and a uniform mean depth of 4 m was modeled using 21 nodes and 20 links. At the open boundary, a tide was specified:

$$y = a \sin \omega_p t \quad (40)$$

where

y = tidal elevation above datum

a = tidal amplitude

ω_f = tidal frequency = $2\pi/T$

t = time

T = tidal period

The solution, neglecting bottom friction and nonlinear accelerations, is (Wang and Connor 1975):

$$u = -\frac{a\sqrt{gh}}{h \cos \omega_f \frac{L}{\sqrt{gh}}} \sin \left[\omega_f \frac{L}{\sqrt{gh}} \left(\frac{x}{L} - 1 \right) \right] \cos \omega_f t \quad (41)$$

$$y = \frac{a}{\cos \omega_f \frac{L}{\sqrt{gh}}} \cos \left[\omega_f \frac{L}{\sqrt{gh}} \left(\frac{x}{L} - 1 \right) \right] \sin \omega_f t \quad (42)$$

where

u = tidal velocity

h = depth of channel below mean tide elevation

g = acceleration due to gravity = 9.81 m/sec^2

L = length of channel

x = distance along channel from tidal entrance

Using a tidal amplitude of $a = 0.1 \text{ m}$ and a tidal period of $T = 600 \text{ secs}$, the model was run. The results for tidal elevations and velocities in 1-D frictionless channels are shown in Figures 29 and 30, respectively. These figures illustrate that the model tends towards the analytical solution. This is a severe test in that there is no damping due to friction, which is an important part of most physical systems, particularly shallow wetlands. However, it serves to demonstrate that the model reproduces the essential features of the hydrodynamic system.

The channel used in Test 2 was also used in Test 3. There was no tidal forcing. Instead, a steady wind forcing of $0.0981 \text{ m}^2/\text{sec}^2$ was specified (Wang and Connor 1975). Figure 31 shows a comparison between theoretical and computed surface water elevations at the closed end of the system ($x = 200 \text{ m}$). The results indicate that the model, under wind forcing, is responding as expected.

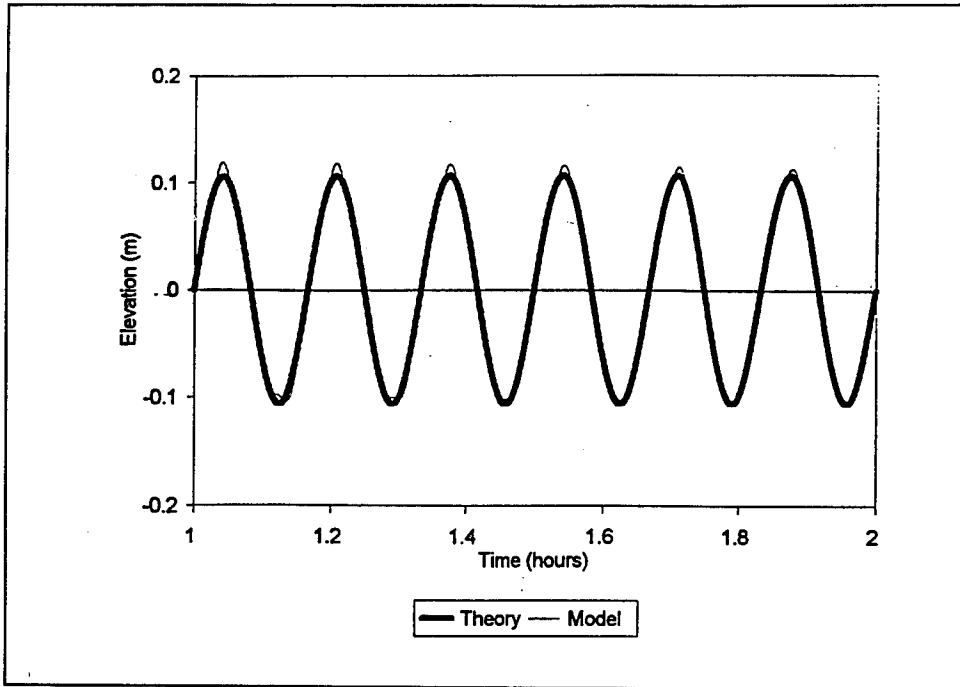


Figure 29. Standing wave elevation in 1-D frictionless channel

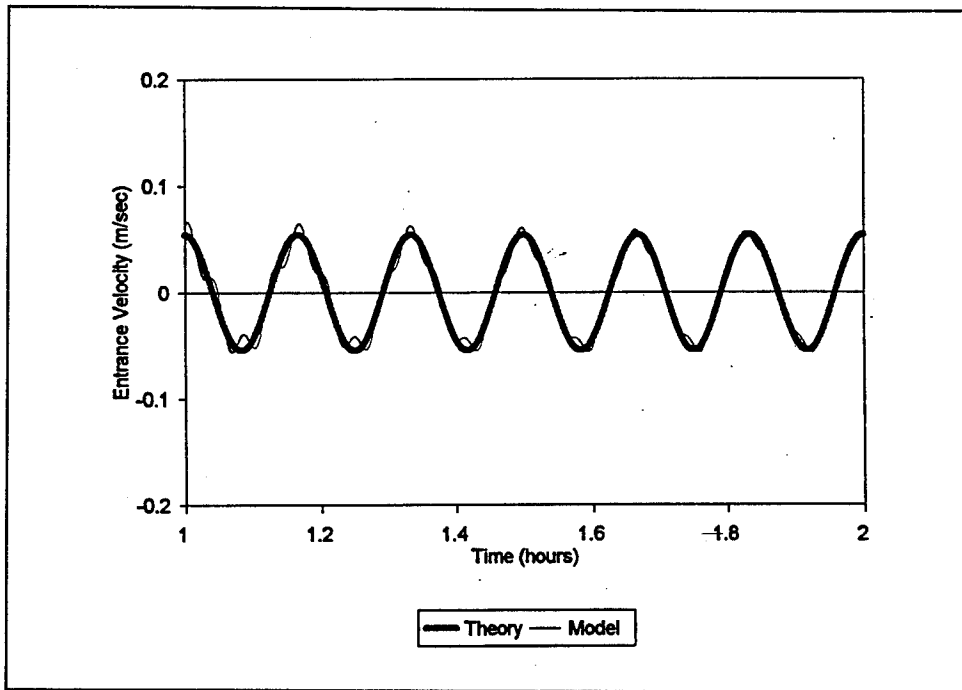


Figure 30. Standing wave velocity in 1-D frictionless channel

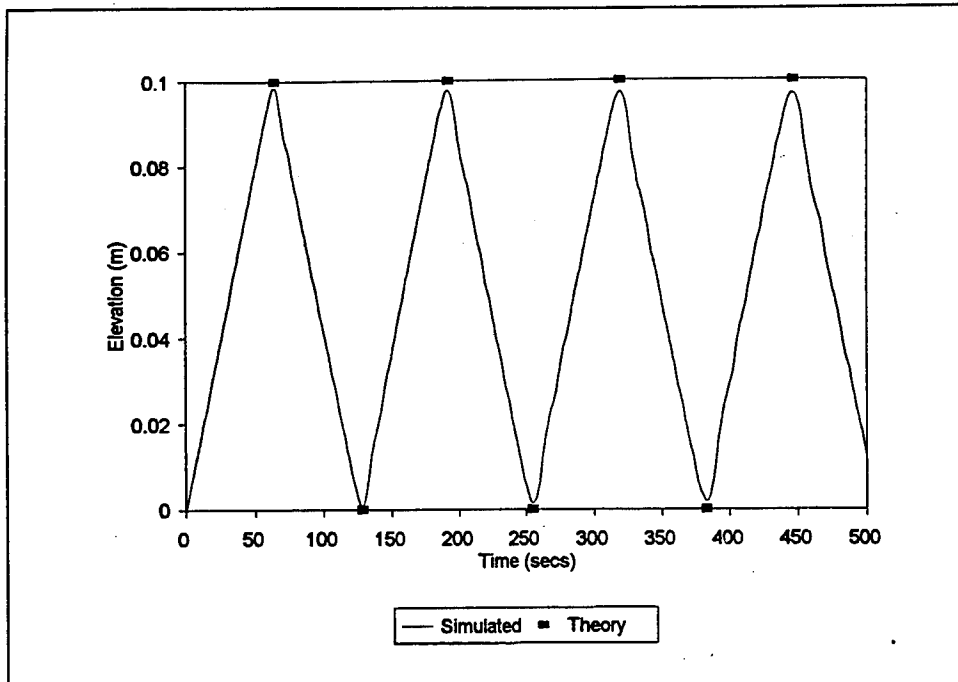


Figure 31. Constant wind shear on 1-D rectangular channel

Vertical Processes

During the course of this study, no suitable analytical solutions that would be an adequate test of the vertical processes module, which includes rainfall, canopy interception, ET, and infiltration, were identified. Instead, a number of simulations were performed and the results examined to determine that the results were “intuitively” consistent.

As much of the vertical module structure was based on the HELP model (Schroeder et al. 1988), Test 4 compared similar simulations from each model. The soil profile was defined to approximate that seen in the Cache River system in Arkansas (see Chapter 7), with 0.9 m of soil overlaying 2.7 m of confining material. In the wetlands model, an underlying sand aquifer with very dry initial conditions was also included to approximate the free drainage from the overlying confining layer assumed in the HELP model. Using meteorology from the HELP model database for Little Rock, AR, and the soil parameters listed in Table 5, Figure 32 compares the actual evapotranspiration computed by each model, and Figure 33 compares the percolation from the base of the confining unit. The HELP model was run using an SCS curve number of 0. However, the model still produced some surface runoff particularly for a rainfall event of about 17.8 cm in 1 day. Consequently, the rainfall input to the Wetlands Dynamic Water Budget Model was adjusted to subtract the surface runoff computed by the HELP model from the rainfall. In spite of differences in the way these models handle some processes (such as surface water runoff and lateral drainage), the results are very similar.

Table 5 HELP—Wetlands Model Parameter Values		
Parameter	Soil Layer	Continuing Layer
Thickness	0.9 m	2.1 m
Residual saturation	0.041	0.04
Field capacity	0.190	0.342
Porosity	0.453	0.471
Hydraulic conductivity	0.00072 cm/sec	0.000042 cm/sec
Soil pore index	0.322	0.151
Soil evaporation coefficient	5.1 mm ^{1/2} /day	5.1 mm ^{1/2} /day
Air suction head	14.66 cm	32.56 cm

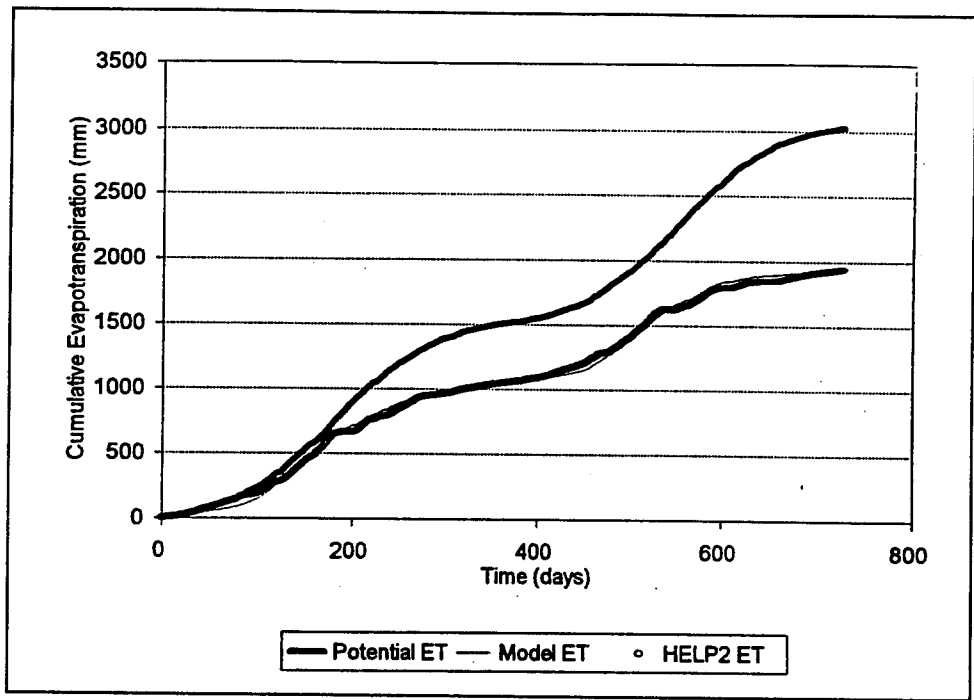


Figure 32. Comparison of evapotranspiration rates

To further test the vertical module, several additional simulations were performed. In the first case (Test 5a), the ground was initially saturated with heads equal to the ground surface elevation. In the second case (Test 5b), the initial heads were 2 m lower (saturated to the base of the confining unit). The results of the simulations were examined in two ways. In both cases, precipitation, air temperatures, and solar radiation data from the meteorological station in the Black Swamp wetlands (see Chapter 3) were used to generate rainfall and evapotranspiration. Using stratigraphic and hydrogeologic

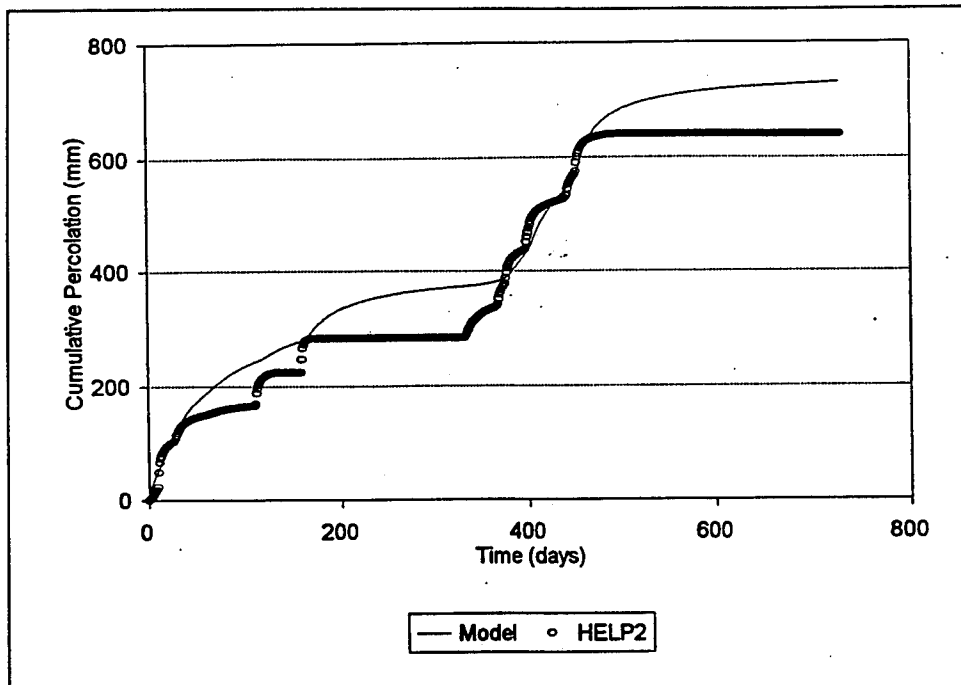


Figure 33. Percolation from confining layer

parameters representative of the Black Swamp wetlands, Test 5 not only examines the differences in infiltration following initially wet and dry conditions but also characterizes the range of infiltration to these wetlands during nonflooding conditions. First, they were examined to ensure that water was being conserved between the various components of the vertical processes. Second, they were examined to determine that the distribution of water was reasonable. Figure 34 shows that, in this case, cumulative rainfall exceeds potential ET_p . For the saturated initial condition, actual ET_a equals potential ET_p (it has nowhere else to go), whereas there is slightly less ET_a for the initially drier condition, as some water infiltrates below the root zone. Infiltration is higher initially for the "drier" case, because water infiltrates to saturate the upper confining layer. Once saturated, the rates parallel each other, indicating an equilibrium balance has been achieved.

Test 6 uses the same model as Test 5, except that the vertical hydraulic conductivity of the upper confining layer is increased by an order of magnitude. Other soil properties were altered to reflect this type of soil. The results, shown in Figure 35, compare the "compact" and "looser" confining unit, for conditions in which the initial heads in all model layers were set to 2 m below the ground surface. The results were again examined for conservation of mass and reasonableness. Examination of Figure 35 shows that the actual ET is essentially the same in both cases, because some water infiltrates below the root zone depth. Infiltration in the looser soil is greater, indicating that water is removed more from the root zone rather than from standing surface water.

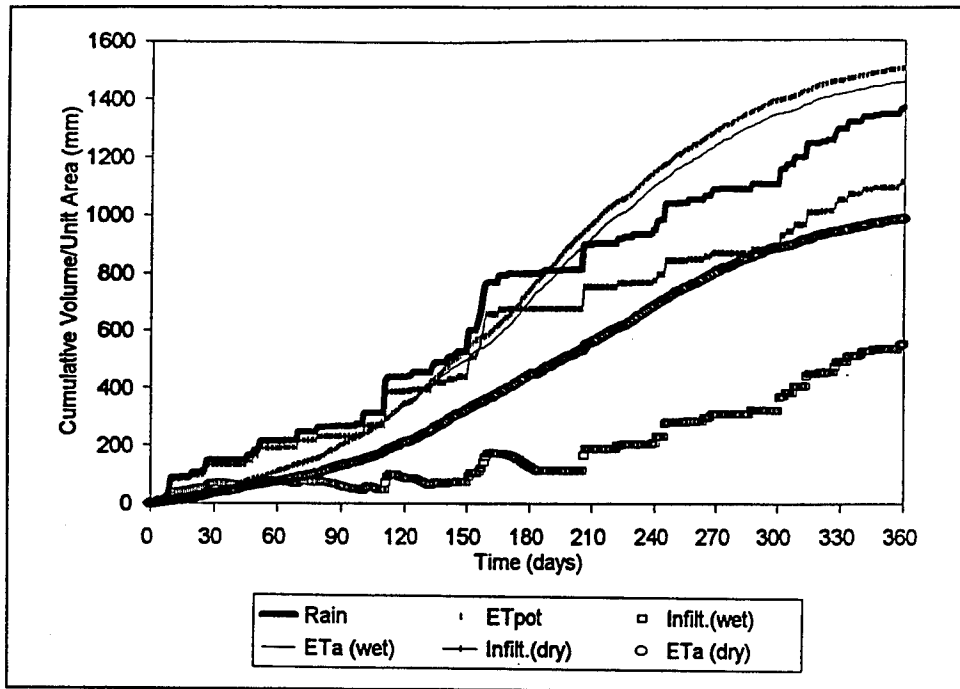


Figure 34. Dry versus wet initial conditions

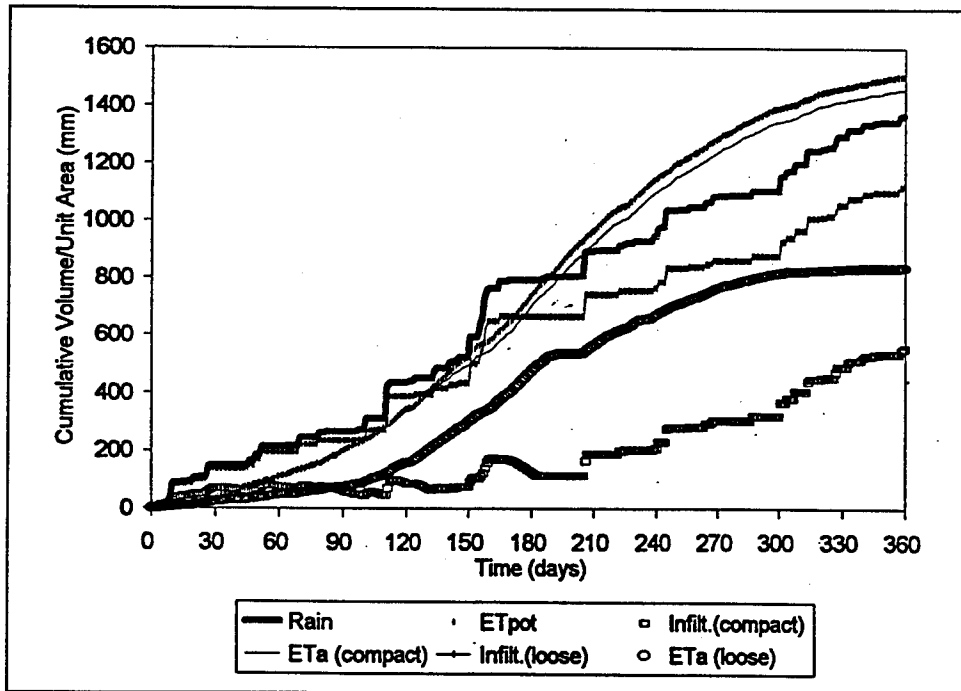


Figure 35. Compact versus loose confining layer

Although model comparisons with analytical solutions have not been shown to “prove” the model formulation, the tests performed illustrate that the model displays expected responses. In all cases, water mass was conserved, and the distribution between the various component processes was reasonable.

Horizontal Groundwater Flow

The groundwater flow module was intended to simulate horizontal flow along the same link-node system as used by the surface water module. To test this module, several simulations were run.

In Test 7, 11 nodes, 10 links, and 6 vertical layers were used to simulate a system 1 km long and 20 m deep. The nominal width of the system was 100 m, although the lateral direction was not resolved. The soils were assumed to be isotropic and homogeneous with a hydraulic conductivity of 0.1 cm/sec, and a specific storativity of 0.001. The ground surface was specified at 50 m above datum and the base of the model at 30 m. The upstream heads were set uniformly at 60 m, and the downstream heads were set to 50 m. The analytical solution for this saturated confined system is a linear variation in heads from upstream to downstream. The model accurately simulated this condition.

Test 8 represented radial flow to a well located at the center of a circular island of radius R . The well pumps from a confined aquifer of thickness H at a rate Q . Under these conditions, the analytic solution is (Strack 1989):

$$h = h_0 + \frac{Q}{2\pi k_s H} \ln \left(\frac{r}{R} \right) \quad (43)$$

where

h = potentiometric head at radial distance, r , from well

h_0 = potentiometric head at boundary ($r = R$)

Q = well pumping rate

k_s = saturated horizontal hydraulic conductivity

H = confined aquifer thickness

r = distance from the well

Using $Q = 5,000$ l/min, $k_s = 0.01$ cm/s, $h_0 = 100$ m, and $H = 10$ m, the groundwater module was simulated for $R = 250$ m and 2,500 m, for a slice equal to one-tenth of a circle. The results, shown in Figure 36 for uniform intervals, $dr = R/25$, show good agreement between analytic and computed solutions.

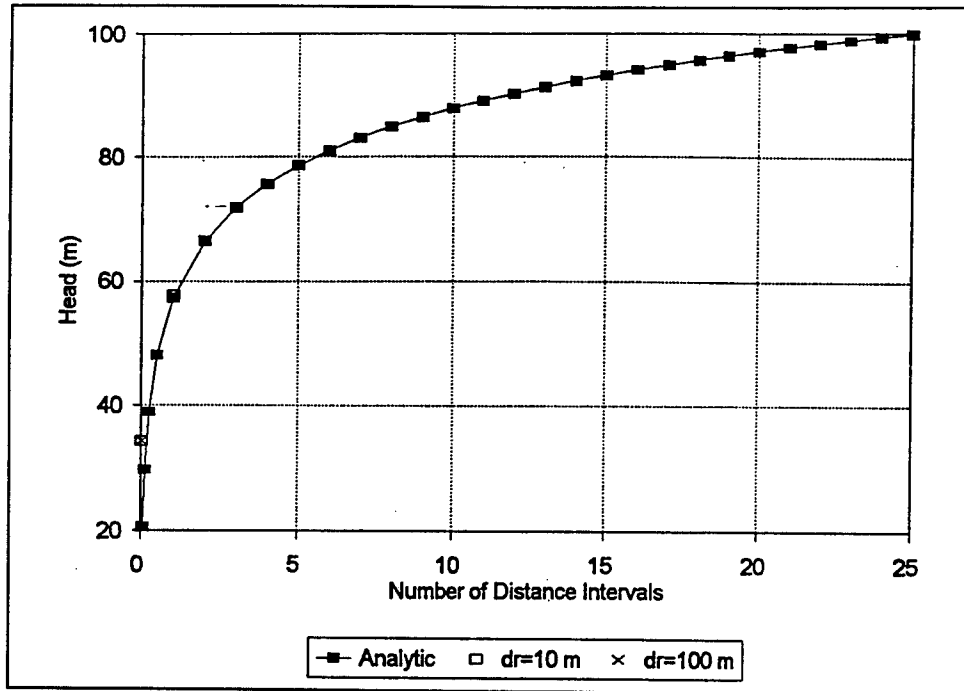


Figure 36. Heads for radial flow to well in a confined aquifer

6 PC Module

In addition to the Wetlands Dynamic Water Budget Model, a PC module has been developed to assist users in model setup, execution, calibration, and manipulation of output. The module uses graphic routines from the Microsoft FORTRAN library, and a routine developed by the Structures Laboratory, WES, as part of HGRAPH, to capture and process individual key strokes. A flowchart illustrating the components of the PC module is shown in Figure 37.

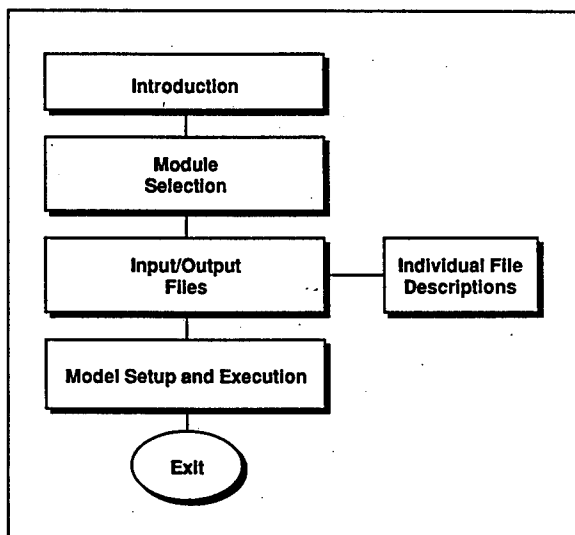


Figure 37. PC Module flowchart

use the **Page Up/Down** keys. Use the **Enter** key to make selections within screens and the **Control_H** keys to obtain "Help" at any time.

SCREEN 2: Permits users to select one or more of the water budget model's modules for their particular application and allows them to define a **project name** (less than nine characters) which becomes the "Root" name for all of the input and output files.

SCREEN 3: Identifies the necessary input files required for the particular application (set of modules) selected by the user. The necessary files are indicated by a "YES" appearing in the box next to the file name. Users can

Overview

The computerized tutorial for running the water budget model uses a sequence of screens to prompt users for information they need for their particular model application. The following is an overview of the screens.

SCREEN 1: Provides instructions for using the screens. To move the cursor around a screen, use the **TAB** or **ARROW** keys. To move from one screen to the next,

view examples of the format for a file's data by selecting (**Enter** key) the file while the cursor is positioned by the file name. The user can also get more information regarding data sources by pressing the **Control_D** keys. The names of the output files that the water budget model will generate are identified by the word "**OUT**" next to the file name. The "**Make File**" option will automatically generate a file list (called "**Root**") which the water budget model uses to identify which files are input files and which are output files.

SCREEN 4: Tells the user how to setup the input data, calibrate and run the model, and manipulate the output data. When the user exits this screen, the tutorial ends. The user may also exit the tutorial at any time by pressing the **END** key.

The following chapters discuss the individual module components of the tutorial.

Surface Water Module Selection

By selecting the surface water module (from **SCREEN 2**) for their model application, users can simulate surface water processes such as channel flow, overbank wetting and drying, remote-basin inflow, tidal forcing, local rainfall, and wind forcing. **SCREEN 3** of the program will enable the following file names (i.e., a "**YES**" will appear next to the file names in **SCREEN 3**):

- **Root.OUT** - general output file to which model input and run information are written.
- **Root.PAR** - run parameter file where module selection; simulation start date, duration, time-step; print initiation and interval; and echo print options are given.
- **Root.GRD** - grid file where the number, location, size, and shape of nodes and links; the linkage between nodes; and link elevation, inverse side slope, and type are defined.
- **Root.ELV** - contains the bottom and overbank elevations of each node.
- **Root.PRP** - defines link properties such as friction formulation and weir and culvert coefficients.
- **Root.INI** - specifies the initial nodal stages or water elevations above the model datum.

- **Root.BCI** - specifies the upstream and downstream boundary conditions (e.g., stage, flow, loop rating, or stage-discharge).
- **Root.HBC** - time series of stages or surface water elevations at each head boundary node specified in file "**Root.BCI**."
- **Root.FBC** - provides the time series of flows or discharges at each flow boundary node specified in file "**Root.BCI**."
- **Root.MET** - contains daily meteorological inputs such as rainfall, temperature, solar radiation, and wind speed and direction.
- **Root.HDS** - nodal head or elevation output file.
- **Root.FLO** - link flow or discharge output file.
- **Root.VOL** - nodal volume output file.
- **Root.VEL** - link velocity output file.

When in SCREEN 3, examples of the input files may be viewed by moving the cursor to the box next to the file of choice and pressing the **ENTER** key. A sample input file is displayed showing the free-field file format, file delimiters, and a description of each variable within a "Help" window at the bottom of the screen. While a sample input file is being displayed, pressing **Control_D** will display brief information on possible data sources for the necessary file data. The "**Make File**" option generates a file called "**Root**" that contains the file names of all the input and output files required for a surface water module simulation.

Note that while examining the data structure for "**Root.GRD**," the user can press the **Control_F** keys to display schematics of the geometry used to describe nodes or links. The figures will be displayed in conjunction with the appropriate line in the data file "**Root.GRD**."

Vertical Processes Module Selection

By selecting the vertical processes module (from SCREEN 2) for the model application, users can simulate processes such as canopy interception, ET, and infiltration. To prescribe inputs and boundary conditions for these processes, the following files are enabled (i.e., a "YES" will appear next to the file names on SCREEN 3).

- **Root.OUT** - general file to which input and run information are written.
- **Root.PAR** - run parameter file where module selection; simulation start date, duration, time-step; print initiation and interval; and echo print options are specified.
- **Root.GRD** - grid file where the number, location, size, and shape of nodes and links as well as the linkage between nodes are defined.
- **Root.ELV** - bottom and overbank elevations of each node, and the elevations of the bottoms of each layer at each node.
- **Root.NOD** - canopy and soil types used in each node layer at each node.
- **Root.CAN** - canopy type in terms of drainage parameters and monthly values of leaf area index (LAI).
- **Root.SOL** - soil type in terms of moisture parameters, hydraulic conductivities, and the power function relationship to soil moisture tension.
- **Root.INI** - initial nodal water surface elevations and groundwater heads in each layer, with respect to the model datum.
- **Root.MET** - daily meteorological inputs such as rainfall, temperature, solar radiation, and wind speed and direction.
- **Root.HDS** - nodal surface water head output file.
- **Root.GWH** - nodal groundwater heads output file.
- **Root.SMC** - nodal soil moisture content output file.
- **Root.SUM** - vertical water mass balance file.

When in SCREEN 3, examples of the input files may be viewed by moving the cursor to the file of choice and pressing **Enter**. A sample file will appear showing the free-field file format, file delimiters, and a description of each variable within a "Help" window at the bottom of the screen. While the sample input file is displayed, pressing the **Control_D** keys will show some general information on possible sources for the necessary file data. The "Make File" option generates a file called "Root" that contains the file names

of all of the input and output required for a vertical processes module simulation.

Horizontal Groundwater Module Selection

By selecting the horizontal groundwater flow module, users can include that hydrologic process in their application. The module can be used alone to simulate depth-averaged groundwater flow, although it is important to remember that the module is based on variably saturated groundwater flow theory. More commonly, the module would be used with the vertical processes module (described above) to simulate 3-D groundwater flow and surface exchanges. To prescribe inputs and boundary conditions for these processes, the files "Root.OUT," "Root.PAR," "Root.GRD," "Root.ELV," "Root.NOD," "Root.SOL," "Root.INI," "Root.GWH," and "Root.SMC" are enabled (i.e., a "YES" will appear next to the file names in SCREEN 3) as described above for the vertical processes module. In addition, SCREEN 3 enables "Root.BCI" which specified fixed head boundary conditions and the location of wells.

Model Execution

Once the necessary input data files are created, the selected modules are executed by typing "WDWBM" followed by **Enter** at the DOS prompt. (Note: the prompt must be in the directory where the swamp program resides or the directory must be in the PC Path (see DOS manual).) At the program prompt, enter the "control" file name: "Root" followed by **Enter**. The program will echo the input and output file names and grid manipulation operations as they are completed. During the model simulation, the program prints a message to the screen each time output data are written. When "SIMULATION COMPLETED" appears on the screen, execution ends.

Output Manipulation

A postprocessing program (called **WDWBMAID**) is available with the water budget model. The program allows users to customize the output data from the surface water module output files. After starting the **WDWBMAID** program, the following data manipulation options are displayed:

1. Create file with specified node numbers
2. Compare computed and observed heads
3. Compare computed and observed flows
4. Select a node or link for graphics
5. Edit heads for initial conditions
6. Convert grid files to new datum and units
7. Hydroperiod statistics
8. Water surface profiles
9. Add more columns of data to file
10. Groundwater heads for graphics
11. Calculate head from soil moisture content
99. EXIT

Enter selection: _____

Use of the options presented above allows the user to generate output files that are easily imported into graphics routines for display.

7 Cache River Simulations

Model Grid

A link-node grid was developed for the Black Swamp portion of the Cache River, consisting of 23 main-channel nodes, and 43 overbank nodes, for a total of 66 nodes (Figure 38). The nodes are connected using 115 links. Along the wider parts of the system, where overbank flows are more likely and very common, parallel links are used. These links consist of one narrow, relatively deep link representing the main channel and a second wide, relatively shallow link defining the immediate overbank area where flow travels parallel to the main channel. Some links and nodes represent storage.

Model Calibration

The surface water module of the Wetlands Dynamic Water Budget Model was driven by upstream flows at the USGS gauge at Patterson and by water surface elevations (stages) at the USGS gauge at Cotton Plant (Figure 38). Data from Water Year 1990 at the other gauges were arbitrarily chosen to calibrate the model. Calibration was achieved by adjusting friction coefficient values (Manning's "n") and by closely reexamining system geometry. The remaining periods of record (Water Year 1988 to Water Year 1991) were used as model validation. The model was run using the dynamic wave equation for the main channel links and the diffusion wave equation for all overbank links.

Figures 39 through 42 show the results of the calibrated model for stages at Patterson, stages at the B5 gauge, stages at James Ferry, and flows at the Cotton Plant gauge. These figures show that the model accurately simulates both the inbank and overbank water levels and downstream flows. In Figure 40, the main stem node adjacent to Transect B was used for comparison to illustrate the wetting and drying of the B5 location. The elevation at B5 is approximately 54.6 m and is seen in Figure 40 as the minimum observed stage.

Another way of evaluating the model simulation is shown in Figures 43 and 44, where observed versus simulated stages are shown for the B5 and James

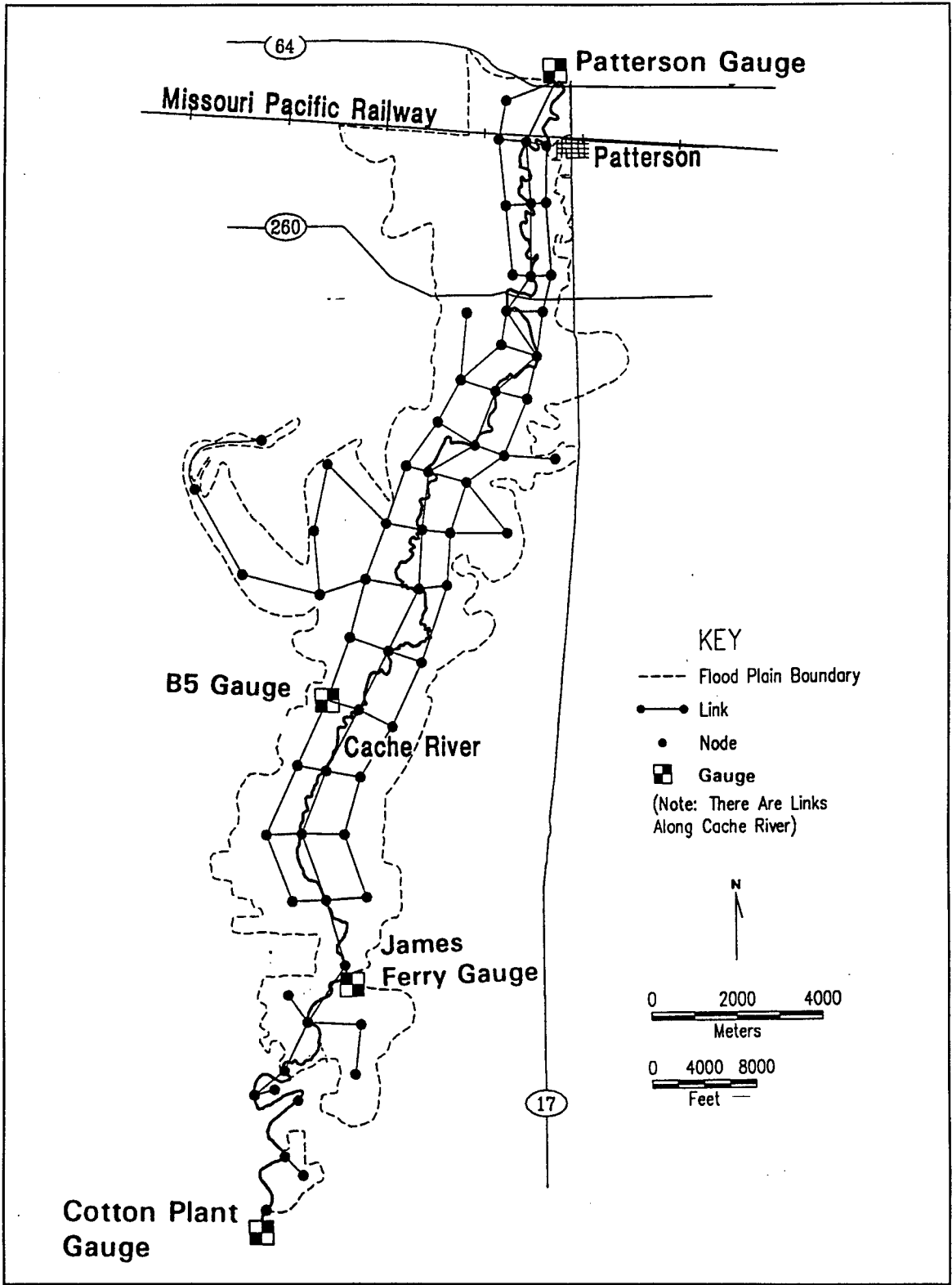


Figure 38. Cache River link-node network

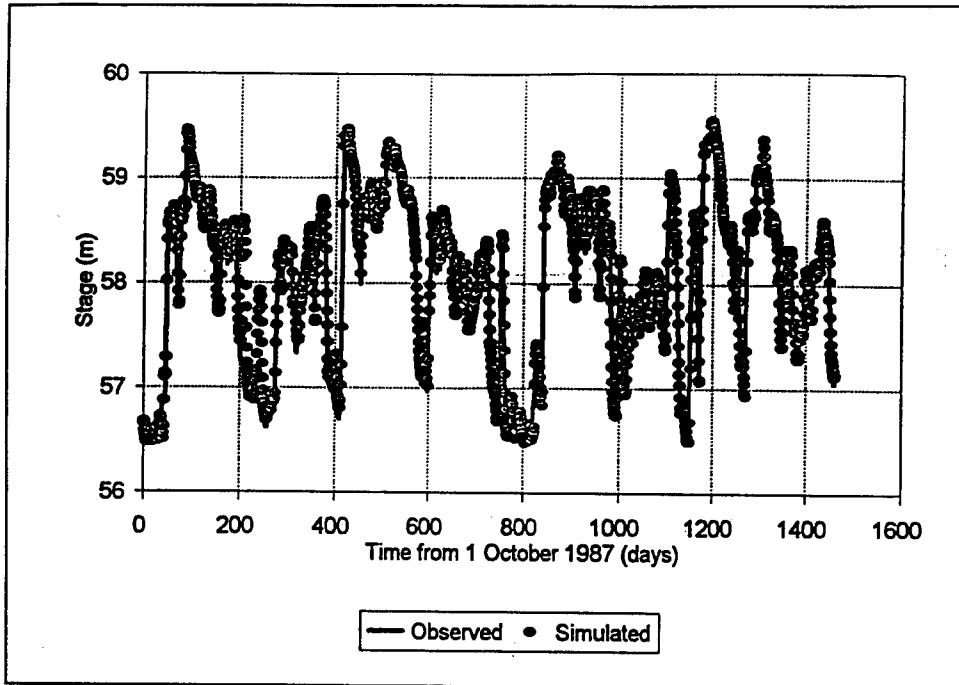


Figure 39. Comparison of stages at Patterson gauge

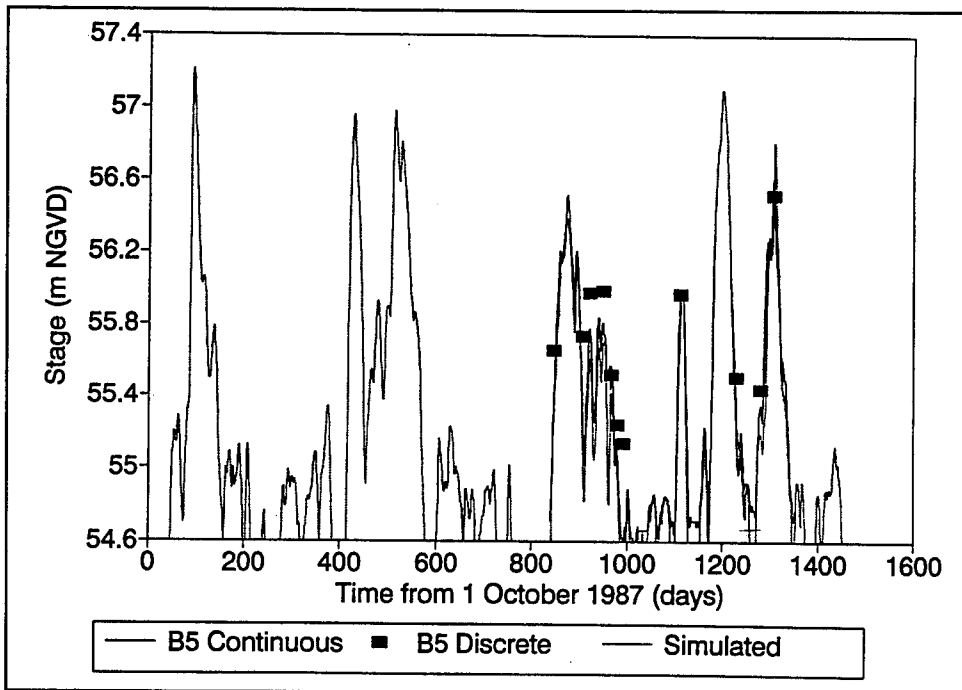


Figure 40. Comparison of stages of B5 gauge

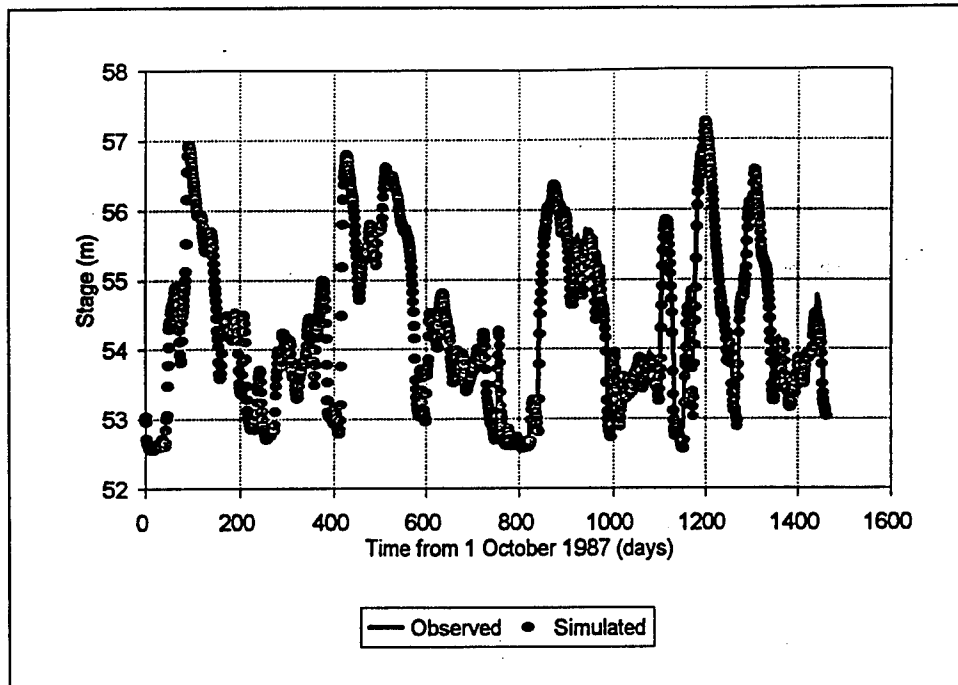


Figure 41. Comparison of stages at James Ferry

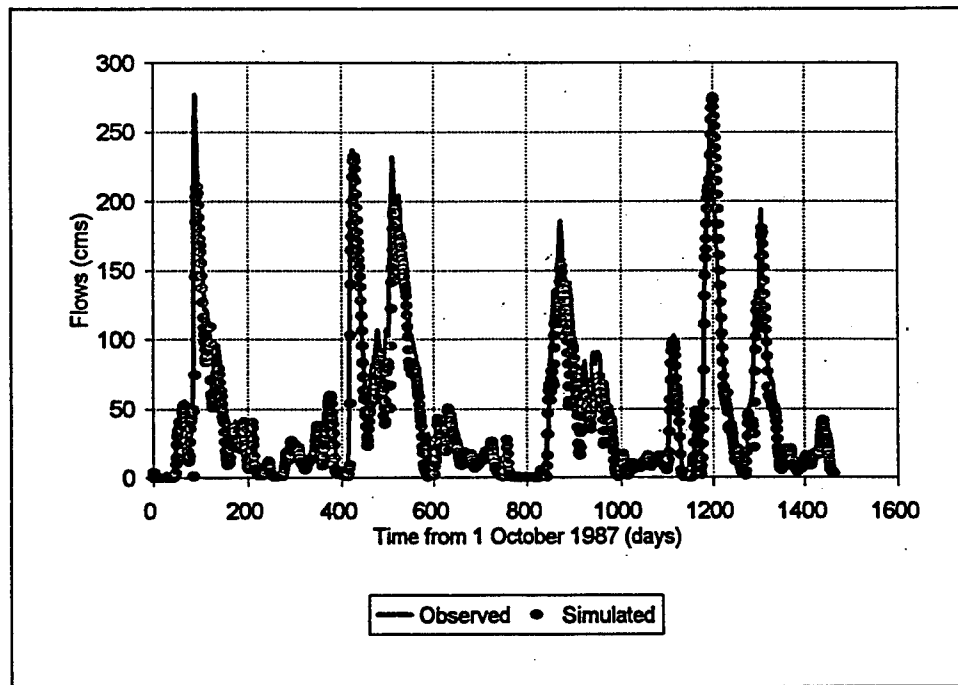


Figure 42. Comparison of flows at Cotton Plant

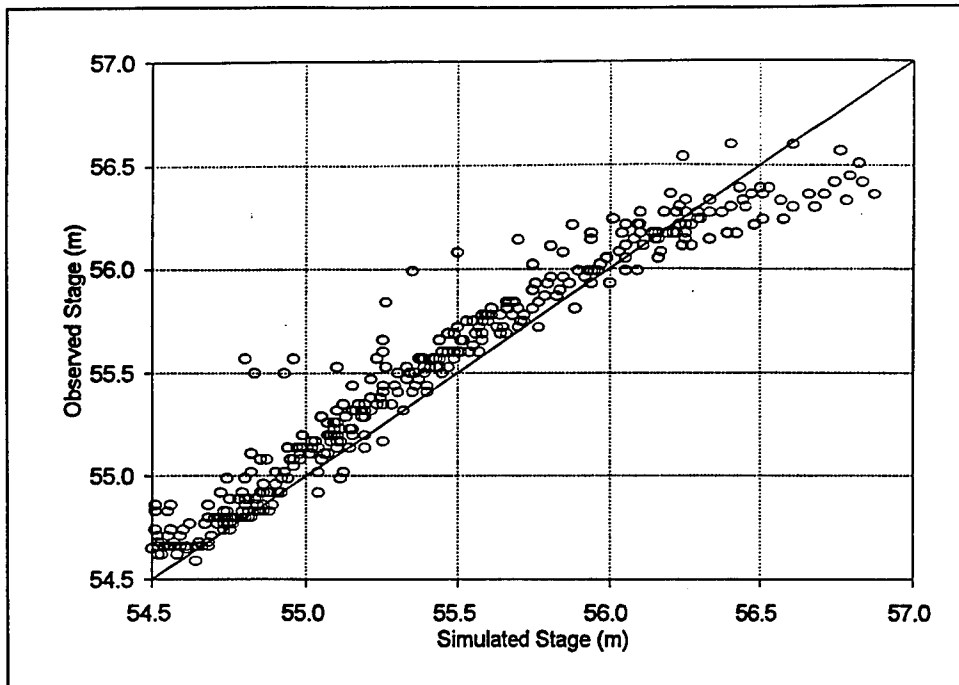


Figure 43. Simulated versus observed stages at B5 transect station

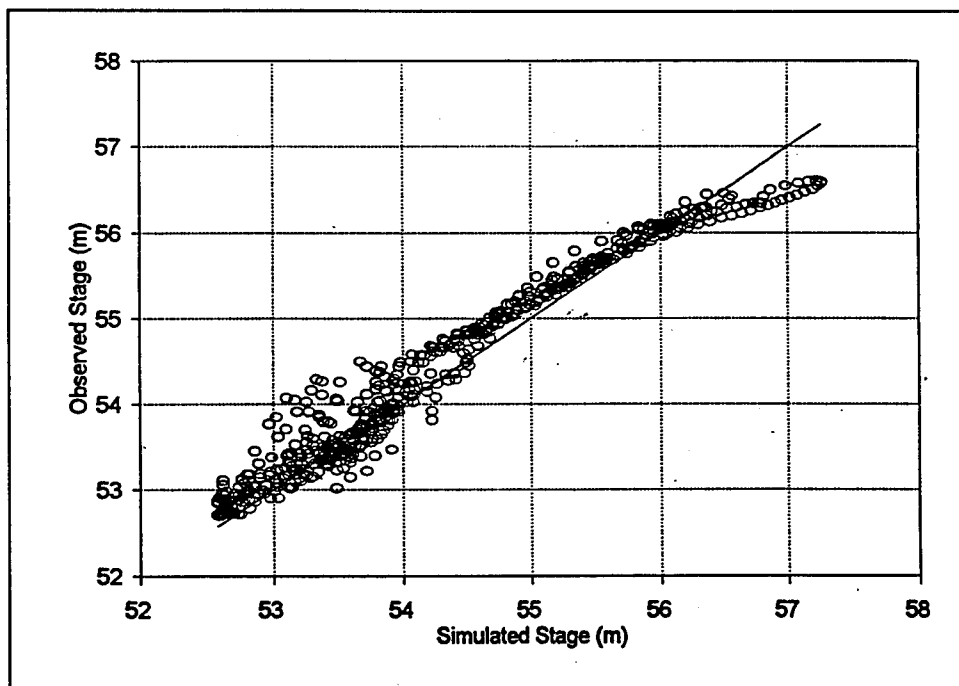


Figure 44. Simulated versus observed stages at James Ferry

Ferry locations, respectively. These figures show that the model accurately simulates inbank conditions, and reasonably simulates overbank conditions up to the extreme events. Figure 44 illustrates that the stages for the extreme events are overpredicted, suggesting either that the extent of flooding is greater than actually simulated, or that the gauges (any, or all of them) had problems recording the extreme events. This latter case is evident at the B5 location where the gauge failed during the largest event on record, and it is possible that rating curves, used to estimate flows at Patterson, are less accurate for these extreme events.

Finally, observed and computed hydroperiods are compared at the B5 gauge location (Figure 45). This figure confirms that the distribution of model results agree well with observations. The small discrepancy at smaller water depths is possibly due to local depression storage on the floodplain not explicitly included in the model.

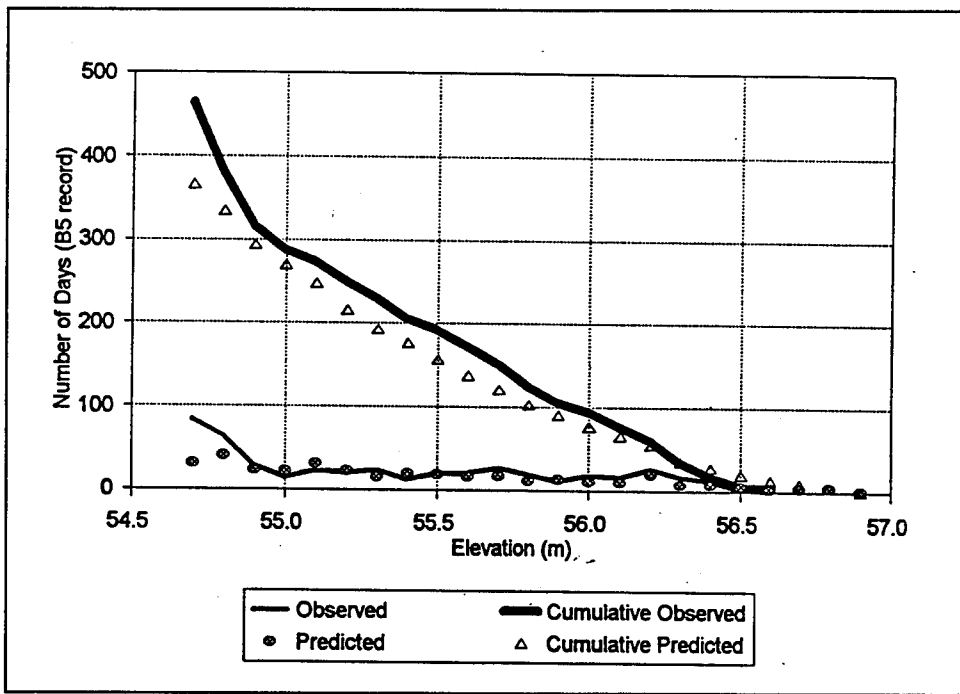


Figure 45. Hydroperiod statistics at B5 gauge

A database was developed from the model simulations that provides additional information to support field data collection efforts. The database contains histories of stage and volume at each of the 66 nodes in the model, and histories of flows and velocities at each of the 115 links. The information developed from the model simulation was used, for example, to examine the frequency of inundation at the B5 gauge location (Figure 45). Aside from the ability of the model to extend the existing field information to provide spatial coverage that is useful for synoptic interpretation of wetland conditions, it can also be used to provide temporal information. This ability enables interpretation of the system between discrete sampling periods and during periods of

instrument failure, such as during January 1991 (Figure 40), when the water level over topped the B5 gauge at about simulation day 1,200.

Model Sensitivity

The surface water module of the Wetlands Dynamic Water Budget Model has the ability to use either the dynamic wave or diffusion wave equation methods for individual links. In addition, culverts, weirs, and other hydraulic structures can be included by replacing the momentum equation in a given link with a formulation for the structure to be modeled. The model was run to simulate two conditions: (a) all the model links using the dynamic wave equation and (b) all the links on the overbank areas using the diffusion wave equation. The results of the two simulations were almost identical. However, it was necessary to shorten the time-step from the theoretical Courant limit for the diffusion wave equation model to eliminate instabilities. This finding confirms the work of Hromadka and Yen (1986) and might lead to later reformulation of the method to provide better stability properties.

The modeling exercise provided insight into the H&H processes that control the Cache River wetland system. First, it was confirmed that there is a significant backwater effect resulting from the constriction in the overbank system near James Ferry. Flooding within the Black Swamp is generally produced by backwater effects from the downstream constrictions, rather than from inundation due to the propagation or downstream advance of the flood wave. Second, flood events on the Cache River typically affect the system for a period of a few days to a few weeks. This time scale is much longer than the time for floodwaters to move laterally over the floodplains, and therefore studies requiring only water level information could perhaps use a 1-D model with complex channel and overbank geometries and conveyances. In such a model, nodes would describe both channel and overbank storage, and only links parallel to the channel need be defined to simulate channel and floodplain flows. However, the quasi-two-dimensional description of the model is very useful in providing lateral variations in hydraulic parameters for other processes, such as water quality and sediment transport.

To examine the effects of vertical process, including infiltration on surface water flows, the surface water and vertical processes modules were used to examine their interaction. Horizontal groundwater flow was not included. A uniform stratigraphy was assumed, based on a draft unpublished USGS study (Gonthier and Kleiss 1994), in which an upper 2-m confining unit was divided into four layers, and a vertical hydraulic conductivity of 0.000042 cm/s used. The underlying sandy aquifer was divided into two additional layers, for a total of six layers representing the upper 20 m of soil. A hydraulic conductivity of 0.07 cm/s was used in the sand aquifer. Initially, the groundwater heads were set below the elevation of the base of the confining unit (2 m below ground surface) and the system simulated.

Figure 46 shows that there is little difference in the downstream flows at Cotton Plant. What little difference there is decreases over time as the underlying soil accepts infiltration and becomes increasingly saturated.

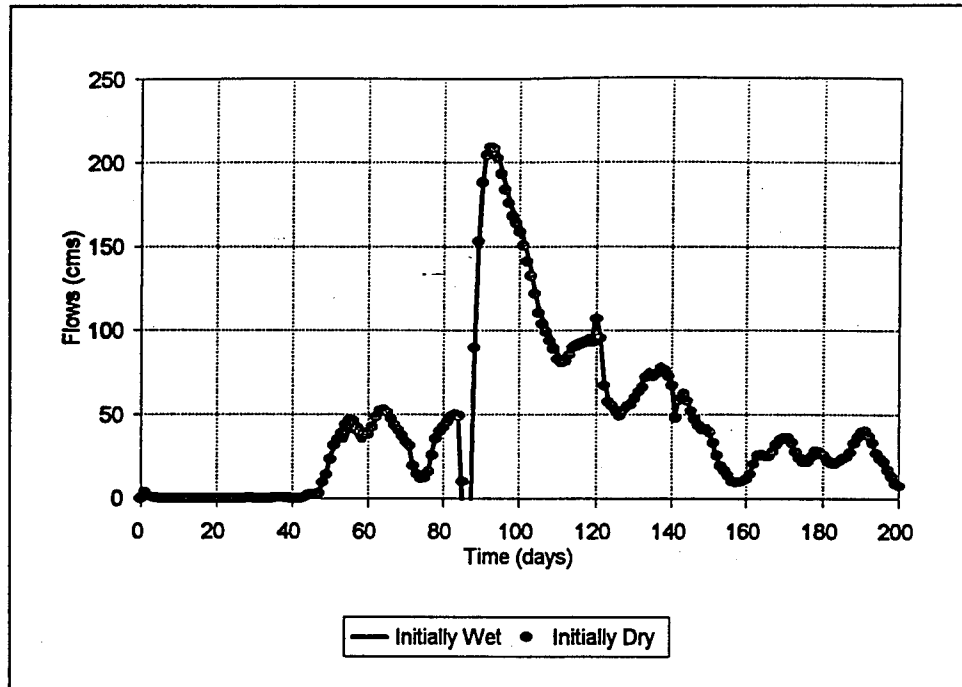


Figure 46. Flows at Cotton Plant in response to floodplain infiltration

Figure 47 shows the response of the overbank node 63 (in the vicinity of the B-Transect) to the first event that goes overbank. This figure shows the quick response of the confining unit to the flood event, followed by a slow drainage to the underlying sandy aquifer. It is also interesting to note that the river heads fall slowly enough that drainage to underlying layers prevents a reversal of vertical heads that would cause a discharge of groundwater to the wetland.

This simulation was merely to illustrate how the model functions. If these simulations were to be used for quantitative purposes, it would be important to first calibrate the groundwater response. Calibrating the groundwater responses requires more data than are currently available and probably also requires including the horizontal groundwater flow module.

Downstream Boundary Conditions

One of the purposes for developing the model is to simulate the response in a variety of wetlands to man-induced changes, such as encroachment, deforestation and restoration, and to investigate the effects of wetland processes on wetland functions. The approach was to develop an analytical tool, the

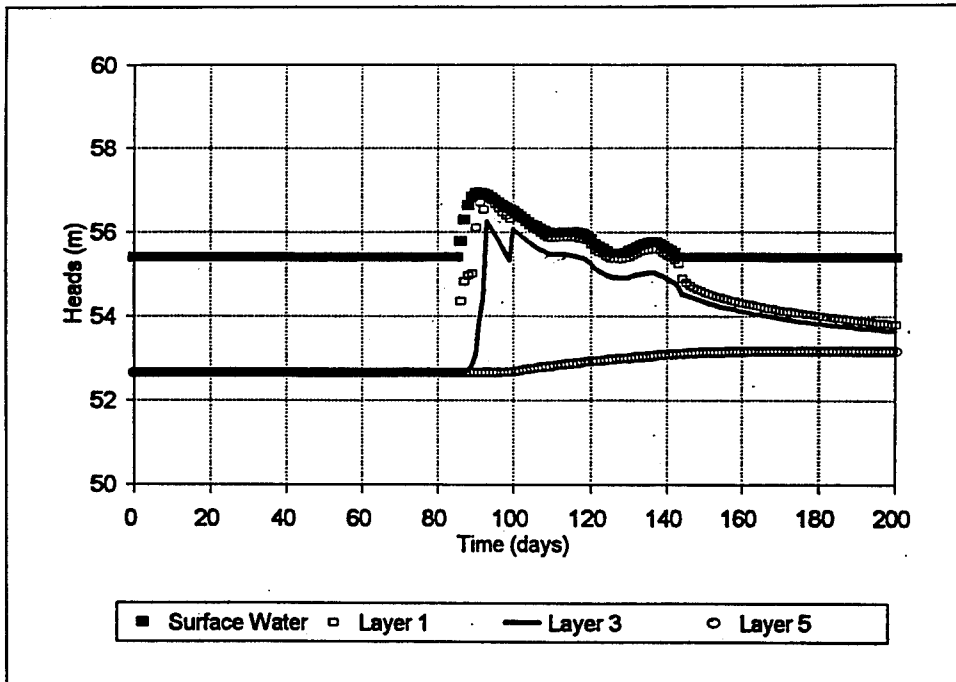


Figure 47. Vertical profiles of heads at B5 gauge in response to floodplain infiltration

Wetlands Dynamic Water Budget Model and to perform a number of “scenario” simulations.

To enable “scenarios” to be accurately simulated, it was necessary to evaluate alternative downstream boundary conditions, because modifications to the wetlands could alter the downstream hydrograph. Three alternative boundary conditions were considered:

- a. A loop rating curve (as the most downstream link has an adverse, or upward, slope, the water surface slope was used instead of the bed slope).
- b. A fourth-order rating curve of the form,

$$Q = 0.0 - 42.03y + 51.66y^2 - 16.71y^3 + 1.756y^4 \quad (44)$$

where

y = water depth (m) at downstream node

was developed from a least-squares fit to observed water depths at Cotton Plant.

c. A rating curve of the form,

$$Q = (H/50.2)^{2.3} \quad (45)$$

The resulting stages at the B5 gauge location (Figure 48) and James Ferry (Figure 49), and the flows at Cotton Plant (Figure 50), show that the fourth-order rating curve had the closest agreement with the calibrated model. This boundary condition was used for subsequent surface water module scenarios.

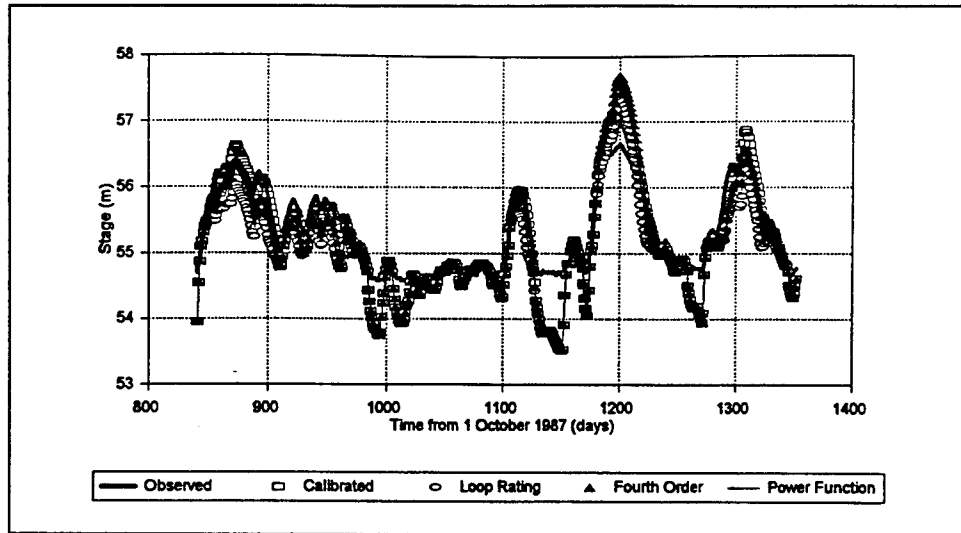


Figure 48. History of stages at B5 gauge for various downstream conditions

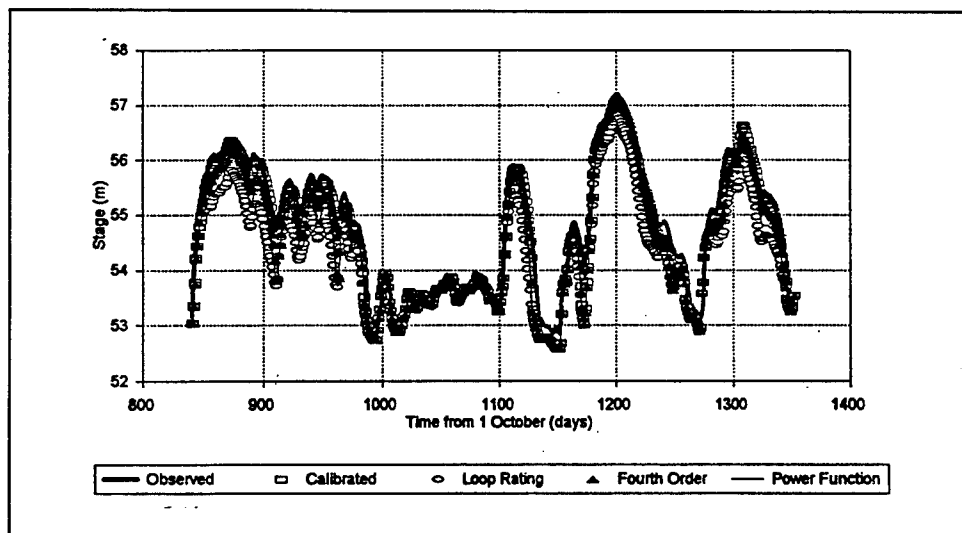


Figure 49. History of stages at James Ferry gauge for various downstream conditions

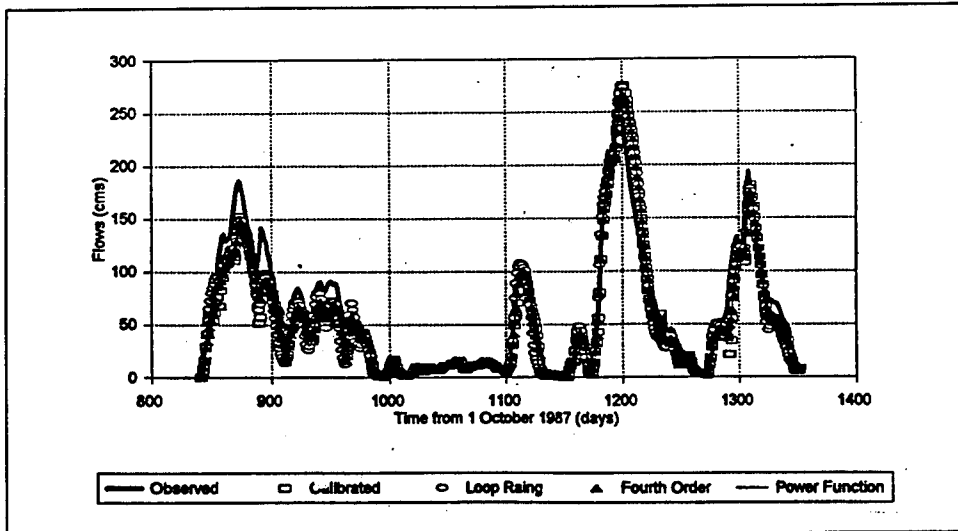


Figure 50. History of stages at Cotton Plant gauge for various downstream conditions

Scenarios

Road construction

A hypothetical road was “constructed” across the Cache River immediately upstream of the B5 gauge location (Figure 51), and four “designs” simulated:

- a. A road that impeded all flow through the system, except for a 20-m opening for the main river.
- b. A road that impeded flow on the distant floodplains but permitted the main river (about 20 m wide) and its immediate floodplain (about 750 m wide) to flow through.
- c. The same as *subparagraph a*, except that a 10-m-wide by 2-m-high box culvert is added on the floodplain on each side of the river.
- d. The same as *subparagraph a*, except that the road’s surface is only 1 m above the floodplain and can be overtopped (simulated using broad-crested weirs on each floodplain).

The calibrated model was run using flows from the USGS gauge at Patterson at the upstream boundary and using the fourth-order rating curve for the downstream boundary. Figures 52 and 53 show the results on the right-descending floodplain, immediately upstream and downstream of the road. The results show that the upstream stages, and therefore the hydroperiods, are directly related to the size of the opening (or overtopping) in the road. Case a,

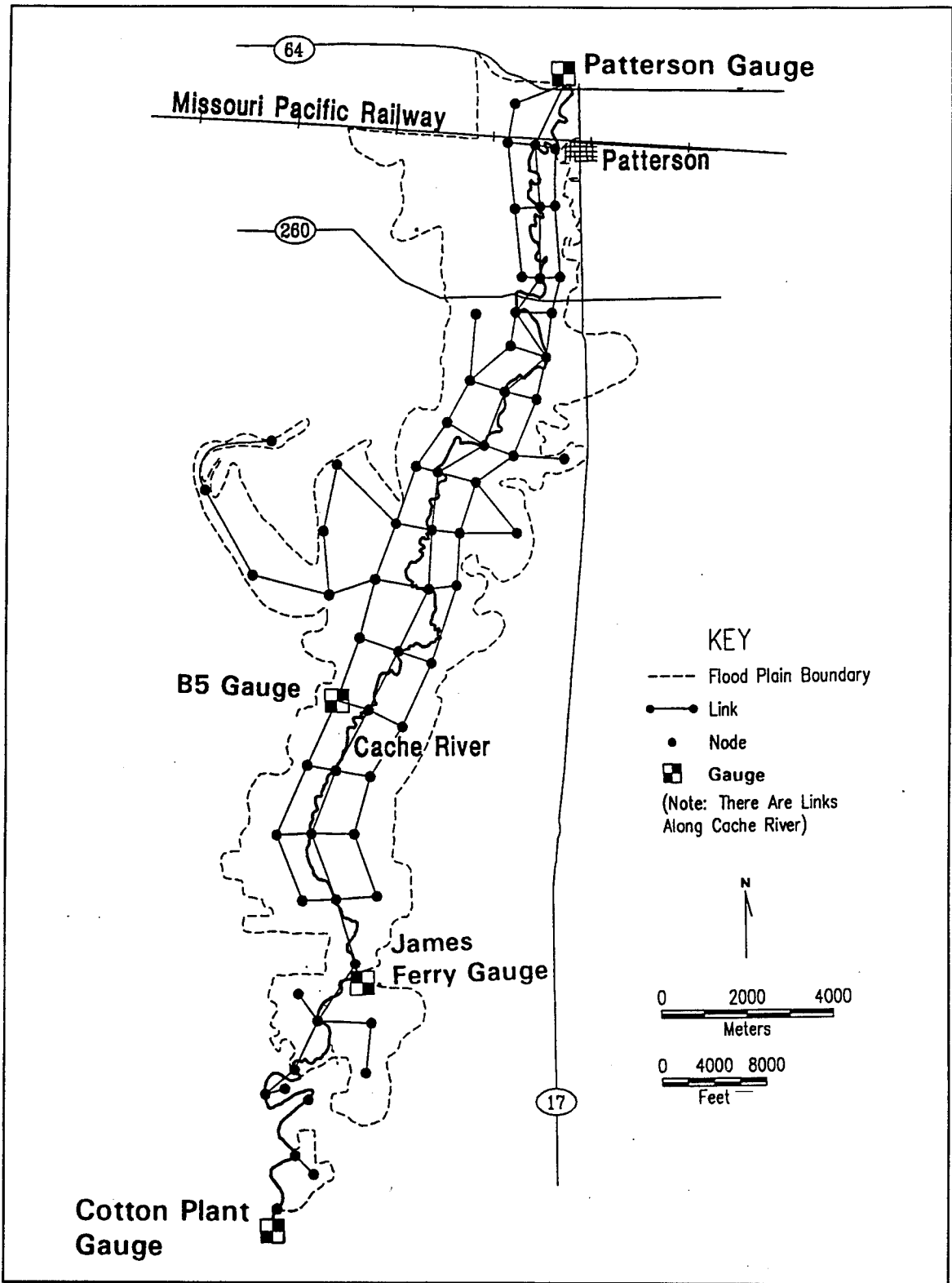


Figure 51. Hypothetical road across the Cache River

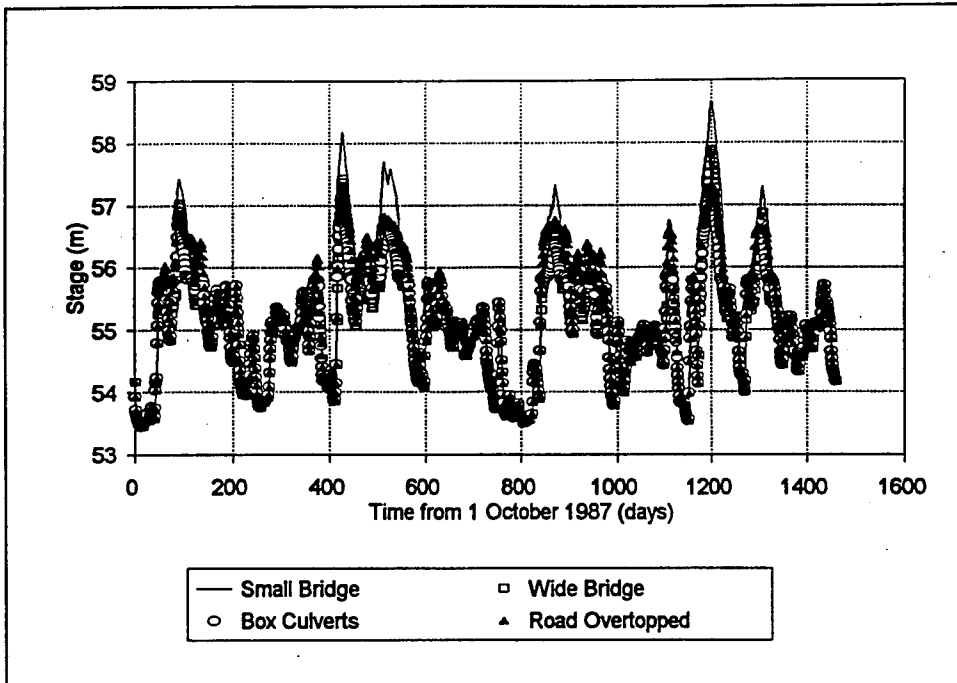


Figure 52. Stages at upstream floodplain node for "road" across Cache River

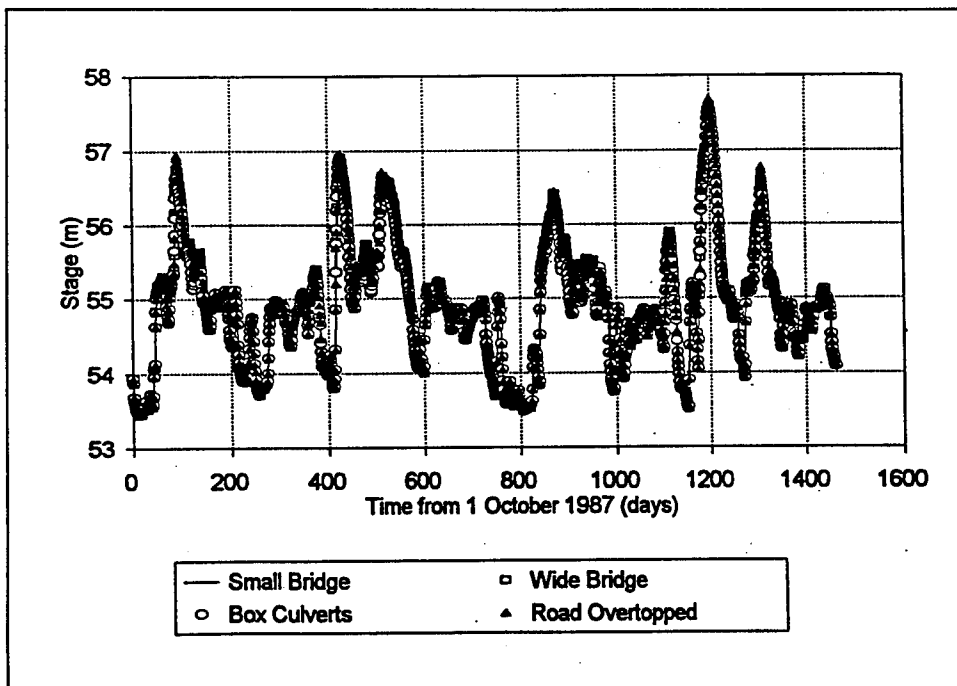


Figure 53. Stages at downstream floodplain node for "road" across Cache River

in which only the main river channel is open, produced the most increase in upstream stages.

At first glance, the downstream response is not immediately clear. In all cases, the stages remain about the same. However, it further illustrates how the system functions. Downstream of the road at James Ferry, and again at Cotton Plant, there are significant restrictions in the floodplain geometry. It appears that these restrictions cause backwater effects that produce much of the upstream flooding in the Cache River wetlands.

When the "road" was added to the system, the upstream stages increased. The higher stages were needed to force through the bridge opening the source flow that occurred without the bridge. This flow produces virtually the same downstream conditions with the two constrictions as produced without the road, highlighting the effect of the downstream controls at James Ferry and Cotton Plant.

Channelized river

In this scenario, two cases were examined. In the first case, levees with side slopes of 3:1 were constructed along the entire river and assumed to be high enough that they are not overtopped. In the second case, the channel is dredged to make the bottom slope more uniform and to increase the bankfull depth (Figure 54).

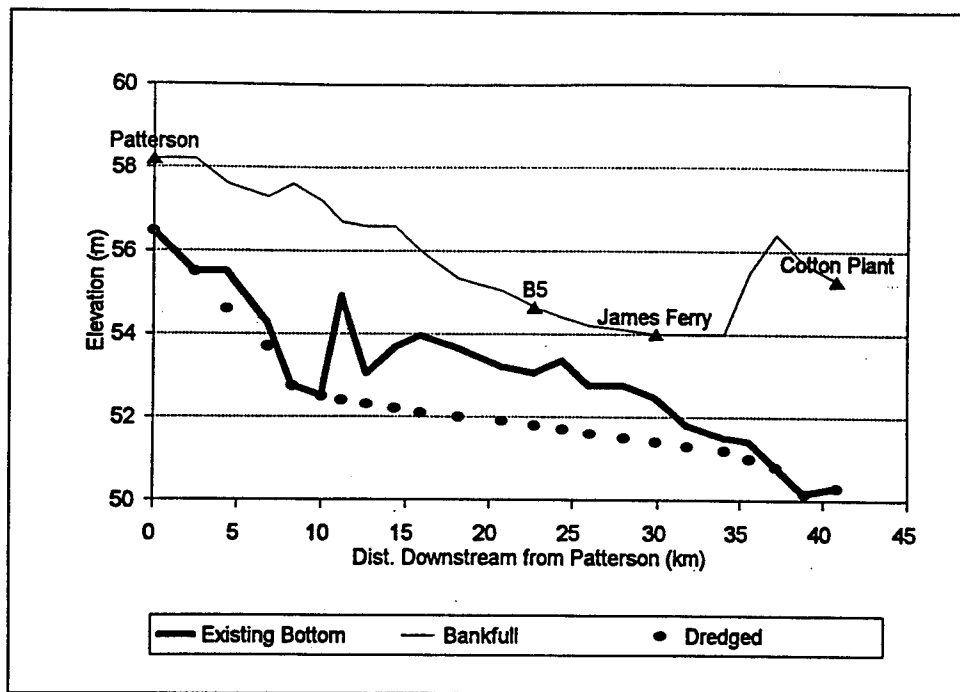


Figure 54. Longitudinal profile of Cache River bottom elevations

The response in the river at higher flows near the B5 gauge location (Figure 55) shows that the levees increase stages here by up to 2 m and increase channel flows and velocities. Dredging has little effect on high flows, probably because bankfull discharges are relatively small compared to major flood flows. However, the results also show that stages are lower during lower flow events, confirming the slight delay in the onset of overbank flood conditions, due to the additional flow capacity of the main channel.

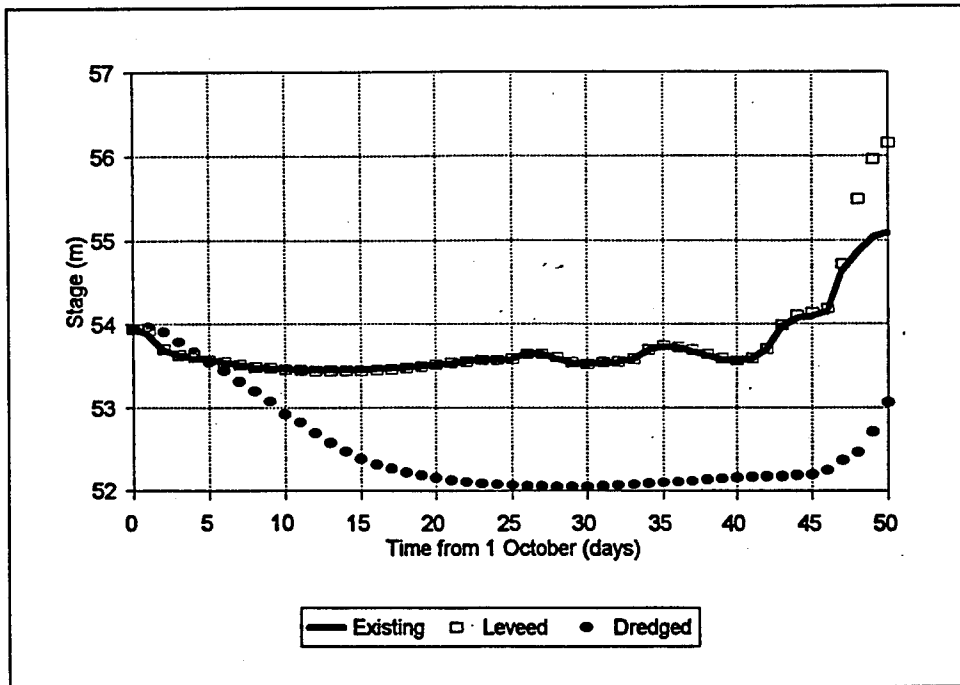


Figure 55. Stages at B5 gauge location for leveed and dredged Cache River

Wetland restoration and enhancement

Immediately upstream of James Ferry, there is a parcel of reclaimed agricultural land surrounded by levees. Two cases of wetland modifications were examined. In the first case, these levees are removed (an additional node, and connecting links were added to represent the modified flow regime). In the second case, the floodplain at James Ferry was further constricted (the overbank link was removed) to possibly increase upstream flooding and hydroperiods.

The response on the floodplain in the vicinity of the B5 gauge (Figure 56) shows that the inclusion of the agricultural area in the wetlands lowers stages by about 8 percent. This is not surprising, since the increase in wetland area was less than 2 percent. The effect of further constricting the flow through the James Ferry area, tends to increase the maximum stages at B5 during major flood events by about 0.2 percent. Again, this is not significant, perhaps, but

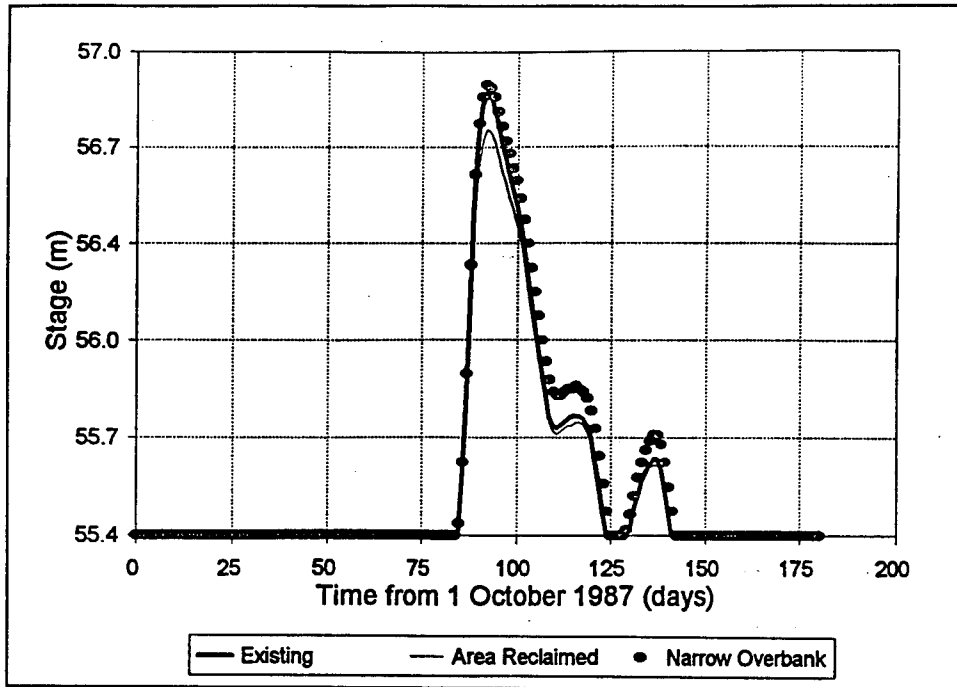


Figure 56. Stages at B5 gauge location for modified wetlands near James Ferry

serves to demonstrate some of the uses of the model in evaluating alterations to existing wetlands.

8 Future Needs in Wetlands Hydraulic and Hydrologic Modeling

A Wetlands Dynamic Water Budget Model has been developed through the WRP to predict the interaction of surface water, groundwater, and vertical transport processes within wetlands. Additional research needed to improve the existing model and allied simplified analyses are discussed below. These analyses include additional model improvements, future applications, and the model's use in developing and verifying simplified methods of wetland H&H analyses.

Model Improvements

The Wetlands Dynamic Water Budget Model was based on a number of models in common use, and many of their theories and approaches are incorporated. An underlying objective was to keep the model relatively simple and efficient, so that it could simulate year-to-year variations. While many of the future model modifications will arise from applications, there are a number of areas that could be studied to improve model accuracy, efficiency, and reliability:

- The current version of the vertical processes module uses a Priestley-Taylor (1972) description of evapotranspiration. This procedure requires knowledge of only air temperature and net solar radiation. More sophisticated methods for estimating evapotranspiration could be examined to assess their effectiveness and data requirements.
- The vertical processes module assumes a saturated flow condition for infiltration across the ground surface. A more exact physical description of unsaturated infiltration could be incorporated into the model.
- There are a number of methods for determining hydraulic conductivity when simulating groundwater flow. It would be useful to examine the effects of these methods on model results.

- An explicit solution algorithm has been used for all modules. It would be useful to examine the computation efficiency and model accuracy when an implicit algorithm is used. This is best tested on the vertical processes module, which can have the most severe stability constraints.
- Data entry could be streamlined by interfacing the model with a geographic information system (GIS). Model geometry could be calculated using a digital elevation model, from which the nodal and link properties could be determined.

Future Applications

To date, the Wetlands Dynamic Water Budget Model has been successfully applied to riverine and estuarine wetlands. As a consequence, it is felt that the surface water routines have been adequately verified. To more completely test the accuracy and adequacy of the remaining process modules, wetlands characterized by primary interactions between horizontal groundwater flow, infiltration, and evapotranspiration need to be examined. The prairie potholes on the northern plains are an excellent example of such wetlands. Finally, the interactions between all the modules can be studied by applying the water budget model at the landscape or watershed basinwide level. At this level, the relative importance of each of the water budget components will vary both spatially and temporally.

The two related issues that must be addressed when applying the link-node model to basinwide applications are spatial resolution and computer time requirements. The Black Swamp application was confined to a relatively small area, and as a result, a fairly fine grid resolution was possible using the fully dynamic equations of motion. However, application of the link-node model to the entire Cache River watershed will require some tradeoffs with respect to the density of nodes and the type of links that are used to connect the node.

Unlike the Black Swamp wetlands, which are influenced almost entirely by river flows, the Cache River watershed is influenced by the amount and spatial distribution of precipitation. In addition, the basin analysis of Chapter 3 indicated that only about one-third of the precipitation is seen as downstream flow. This means that other vertical processes, such as infiltration and evapotranspiration, are important mechanisms working in the watershed. Finally, as infiltration does not all return to the river as baseflow, it is possible that deep groundwater flow is also an important process. A conceptual model of the Cache River watershed would have to initially include all the H&H processes identified for the development of the Wetlands Dynamic Water Budget Model (see Figure 22 in Chapter 4).

Instead of modeling every secondary stream into the Cache River as a series of links and nodes, all but the largest should be modeled as simple exterior basins or subwatersheds. In other words, subwatersheds should be

modeled as a single node with one link to the mainstem of the river. This will allow the use of vertical processes such as precipitation, infiltration, and runoff within the subwatershed while minimizing the computational burden. Furthermore, in well channelized reaches of the Cache River, it is only necessary to place mainstem nodes at the confluence of the subwatershed. This will allow the use of longer links, which relaxes the stability condition on channel flows and thus reduces computer time. The skill of this approach can be evaluated by using the USGS gauge at Patterson to determine if the correct flow is being routed down the river from the upper part of the watershed. Use of the Patterson gauge as a calibration tool will aid in the determination of rainfall intensity distribution, basin runoff, and infiltration characteristics.

Simplified Methods

The successful application of the Wetlands Dynamic Water Budget Model to the Black Swamp area of the Cache River in Arkansas has produced a 4-year database of surface water elevations and flows throughout the wetland. This database, along with the field data collected during the WRP, provides the opportunity to develop and test simplified methods of wetland H&H analyses. For example, correlation functions of computed surface water elevations with available USGS gauge data at Patterson, James Ferry, and Cotton Plant can allow (a) future evaluation of the impacts of flow alteration on the hydroperiod within the Black Swamp and (b) development of an historical database of hydroperiods using the long-term gauge record available at Patterson. Several examples of these regressions are provided in Chapter 3. The regression of the Patterson gauge versus the B5 gauge, using a 2-day time lag, is presented in Figure 21. A companion analysis of hydroperiod, or continuous days above a specified flood stage, at the Patterson gauge is compared with the resulting stage-duration at the B5 gauge in Table 4 (Chapter 3).

Examination of Table 4 suggests that there is a consistent correlation between the hydroperiod of a given storm event recorded at Patterson and the resulting stage and hydroperiod experienced at the B5 gauge. In addition, there is significant backwater or storage effect due the constriction of the flow between James Ferry and Cotton Plant. This is seen in the increased hydroperiod at the B5 gauge. The important point to be made here is that the computed surface elevation database can be used to develop similar correlation functions at any location within the Black Swamp. As a result, more complete and longer-term information on stage and hydroperiod at the other three Cache River research transects can be made available.

A simplified method for performing a wetlands water budget analysis and determining the relative importance of H&H processes can be based on the following balance equation:

$$Q_i + R + G = Q_o + ET + I \quad (46)$$

where

Q_i = surface water flow into system

Q_o = surface water flow out of system

R = direct rainfall on wetland

ET = evapotranspiration from wetland

G = groundwater discharge to wetland

I = infiltration to the groundwater

For many wetlands, these variables can be estimated using simple methods or available data, or both. Surface water inflows can be determined from upstream gauges or from published statistics of river flows. If the basin is ungauged, then it is possible to estimate flows using data from nearby gauged basins and multiplying by the ratio of drainage basin areas, or using published regression analyses (available for many states from the USGS). Downstream flows can be determined using the same approaches, or by using data from control structures such as weirs, gates, and culverts. Flows can be converted to annual volumes/unit area by summing the flow over 1 year and dividing by the surface area of the site. Rainfall data are available from nearby gauges, or published summaries (e.g., annual rainfall maps from NOAA). Potential evapotranspiration data can be found from a number of sources or calculated from atmospheric parameters, such as air temperature and net solar radiation, using formulae such as the Priestley-Taylor method. Groundwater discharge can be estimated from potentiometric head data using Darcy's Law. Maximum potential infiltration can be estimated from percolation tests, sometimes published in local soils reports or from measurements or estimates of saturated hydraulic conductivity based on only a crude knowledge of local soil types. An upper bound can be calculated by multiplying one-half times the saturated hydraulic conductivity by the amount of time the site is estimated to be inundated or receiving rainfall. It should be recognized that this may represent an extreme upper bound as it does not consider other factors, such as the soil becoming fully saturated and unable to receive additional water unless some soil water is removed. It is also important to recognize that Equation 46 can be used to estimate the magnitude of a process with no data, or to provide an alternative estimate for a process (usually groundwater discharge or infiltration) which may be poorly estimated, provided estimates are available for *all* the other processes.

To decide whether each process is important in the hydrology of the wetland being evaluated requires a knowledge of the errors in these estimates and a decision as to when one process dominates another. Typically, river flows can be measured to 5 to 10 percent accuracy if good gauge data are available. Measurements and estimates of the other variables are probably less accurate

in most cases. So, a first-order criterion might be that one process is not significant if it provides less than 10 percent of the flow of another.

To illustrate this procedure, approximate annual water budgets were prepared for the Black Swamp wetlands on the Cache River (Table 3 in Chapter 3), for the Bolsa Chica tidal wetlands (Hales et al. 1990), and for 10 depressional wetlands in North Dakota and Minnesota (Winter 1989). The water budgets are shown in Table 6.

Variable	Annual Volume/Unit Area (m)		
	Cache River	Bolsa Chica	Depressional
Inflow	14	2,600	0.402
Outflow	16	2,600	0.0
Rainfall	1	0.26	0.369
Evapotranspiration	1	1.2	0.643
Groundwater Discharge	<1	30	0.0
Infiltration	<1	29	0.183

For the Black Swamp, infiltration was estimated at about 6 m, assuming reasonable values for saturated hydraulic conductivity and that the wetlands are inundated about one-third of the time. However, this value is probably greatly overestimated as it neglects the saturated soil conditions that would frequently result under these conditions. Therefore, a more reasonable value, shown in Tables 3 and 6, was used based on satisfying the water budget of Equation 46. From this analysis, using a 10-percent criterion, we would conclude that on an annual-average basis only river inflows and outflows are of major importance to the Black Swamp.

For the Bolsa Chica tidal wetlands in Los Angeles (Hales et al. 1990), tidal inflows and outflows were estimated by dividing the tidal prism volume by the area of the wetlands. Rainfall, evapotranspiration, and infiltration were estimated using a very conservative application of the HELP2 model (Schroeder et al. 1988). Even from this rough analysis, it is not surprising that the wetlands are dominated by tidal flows. It may also be important to consider the infrequent influx of fresh water from a flood control canal. This flow can be approximately 50 percent of the tidal flow and changes the saltwater/freshwater balance before it is flushed from the wetlands.

Table 6 indicates that rainfall, inflows, evapotranspiration, and infiltration are important processes in the hydrology of Northern Prairie depressional wetlands, often called prairie potholes. Comprehensive studies of this type of

wetland would probably require quantifying surface water, vertical, and groundwater flow processes.

These analyses were based on data at hand and illustrate the approach to determining which H&H processes are important for each type of wetland. This analysis could be expanded to consider the importance of processes at other time scales, such as the freshwater inflows into the Bolsa Chica tidal wetlands, and to examine the major processes for other types of wetlands.

9 Summary

In their work on cumulative impacts on wetland functions, Nestler and Long (1994) stated that most significant wetland functions can be described completely or in part by hydrologic factors. Underlying this statement is the understanding that the characteristics of wetlands are largely controlled by the hydrologic regime of the wetlands. Similar statements can be found in almost any publication that addresses aspects of wetland hydrology. Hence, a well-founded understanding of wetland hydrology will increase our knowledge of wetland processes and functions.

To advance our understanding of wetland hydrology, the U.S. Army Corps of Engineers established in its Wetlands Research Program an investigation of physical hydrologic processes and the influences of those processes on wetland functions. In addition, the research was intended to develop tools and techniques that might aid in that pursuit. The research which is reported here includes the results of a comprehensive study of wetlands along the Cache River in eastern Arkansas, an investigation of hydraulic and hydrologic wetland processes, the development of a dynamic water budget model and the exploration of simplified techniques for assessing hydrologic characteristics of wetlands.

The field investigation of wetland processes and functions was conducted in the Black Swamp floodplain wetlands of the Cache River between Patterson and Cotton Plant, Arkansas. The Cache River is an underfit stream flowing in an old channel of the present-day Black and St. Francis Rivers. Much of the Cache River upstream of the study area has undergone extensive channelization to allow agricultural development in the basin. The drainage basin of the Cache River upstream of Patterson is 2,686 square km (Neeley 1987). The study area included 350 square km of the lower part of the drainage basin. Approximately 60 square km of the study area are bottomland hardwood forests typical of wooded wetland systems in the lower Mississippi River Valley (Kleiss 1993). The wetlands generally lie within 2 km of the river channel.

The hydrologic measurements in the field study included USGS river gauges at the upstream and downstream limits of the study area (49 river km apart), water level recorders inside the study area a nest of deep and shallow groundwater wells which monitored variations in the underlying aquifer, a

meteorological recording station that collected precipitation, temperature, and solar radiation data inside the study area and regional precipitation data.

A water budget is an important analytic tool for evaluating the dominate hydrologic mechanisms of a wetland. The water budget accounts for all inflows, outflows, and water stored in a wetland. The elements of a water budget include precipitation, evapotranspiration, channelized flow, overland flow, groundwater discharge and infiltration, tidal flow and volume storage. An analysis of the water budget for the Cache River study area showed that the system is dominated by river flows and that the estimated contribution of the other water budget components (e.g., precipitation, groundwater flow, evapotranspiration) is less than 10 percent of the river flow. Since, the errors associated with well maintained river gauges are near 5 to 10 percent, it is difficult to determine whether differences between measured river inflow and outflows can be accounted for by the other water budget components.

The analysis of the Cache River's hydraulic behavior showed that the system is characterized by floods occurring from mid- or late fall to midwinter and again in mid- to late spring. Peak flood flows are about 185 m³/s for a 2-year return event and 270 m³/s for a 5-year event. The peak flows between the upstream and downstream gauges are reduced by about 10 to 20 percent with greater attenuation occurring when the system is drier initially. The flood-peak attenuation between the upstream and downstream gauges is due mainly to floodplain storage with flow resistance contributing little. The peak flow at the downstream gauge lags the peak at the upstream gauge by 4 to 8 days depending on antecedent conditions. The flooding of the overbank areas is the result of constrictions in river channel width in the downstream reaches of the study area. The constriction increases river stages upstream causing water to flow over the low channel banks onto the extensive floodplains.

A dynamic wetland water budget model was developed during this study to support the field investigations. The model was used to provide temporal and spatial information not provided by the field instrumentation. During periods when gauges were not operating or in large regions of wetlands where no gauges were installed, the model was used to generate synthetic data which augmented the actual data. These synthetic data, especially the spatially distributed data, were of great value to researchers studying large scale phenomena like vegetation composition and structure. Often, areas of interest to these researchers were far from hydrologic instrumentation, but the model was able to provide estimates of the hydrology.

The model consists of three modules which include surface water processes, vertical processes, and horizontal groundwater flow. Surface water processes represented in the model include (a) channel and overbank flows, (b) tidal flows, (c) wind forcing, (d) the influence of hydraulic structures like weirs and conduits, and (e) watershed inputs. The vertical processes include (a) precipitation, (b) canopy interception, (c) surface water evaporation, (d) infiltration, (e) transpiration, and (f) soil water evaporation. The groundwater processes

include fixed heads and specified fluxes, such as wells. The model uses an explicit link-node technique and includes many of the algorithms and solution methods found in existing hydrologic and hydraulic models. The model is relatively simple, efficient, and flexible and can be used for the long-term simulations that are often needed in wetland research. The surface water module was extensively tested during the Cache River study because of the dominance of the surface water processes in those wetlands. The data available were insufficient to thoroughly evaluate the vertical processes and horizontal groundwater flow modules. The performance of these modules was qualitatively evaluated.

The model performed well for the riverine studies on the Cache River, and it is expected that the model will work well for other wetland types. The model's link-node formulation and the modular structure make it potentially useful for applications to depressional wetlands like the prairie potholes in the northern plains of the United States and to evaluations of watersheds. Applications of the model to other wetland types (or watersheds) will help evaluate the utility of the model for those applications and can be used to refine its formulation.

The extensive datasets available from the Cache River field and modeling studies made it possible to evaluate simple techniques for assessing a riverine wetland. For example, water levels measured at locations inside the study area were correlated to water levels at either the upstream or downstream river gauges. The data were strongly correlated which suggests that such techniques might be used to rapidly calculate wetland waterlevels based on data from a river gauge. For example, the upstream gauge on the Cache River has a 60 year record of water levels. A good correlation between this gauge and locations with a wetland would allow an approximate determination of water levels for those locations for a 60-year period. A technique which roughly correlates hydroperiod was also proposed.

While the Cache River field study is probably the most comprehensive study of Lower Mississippi Valley bottomland hardwood wetlands and has advanced our understanding of the functioning of these wetlands, additional studies of a similar nature are needed to see if conclusions developed from the Cache River apply to other wetlands. Such comparisons will allow us to identify similarities (or dissimilarities) in wetland functions and will help determine whether simplified techniques developed at one site can be applied equally as well at another.

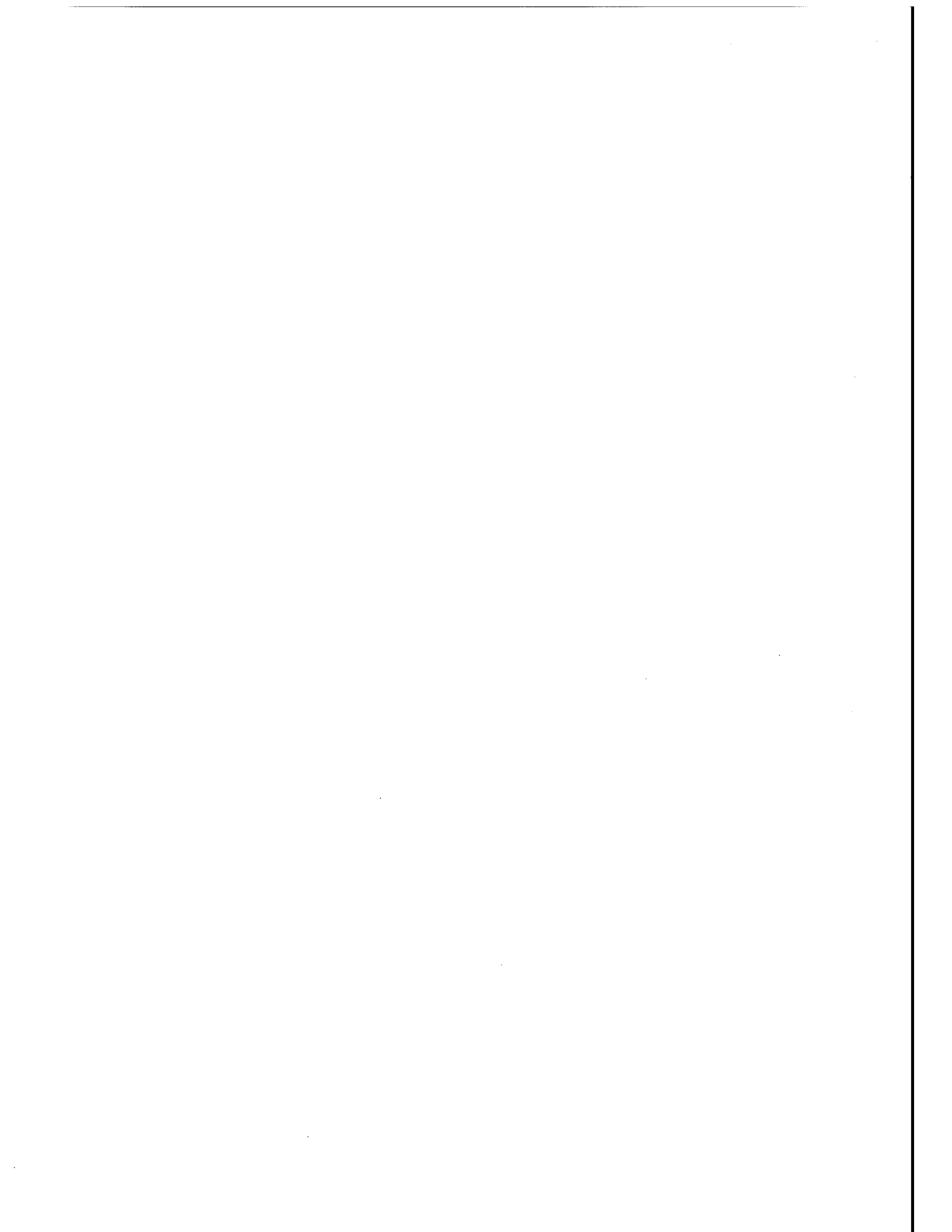
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Appendix A

Cache River Cross Sections

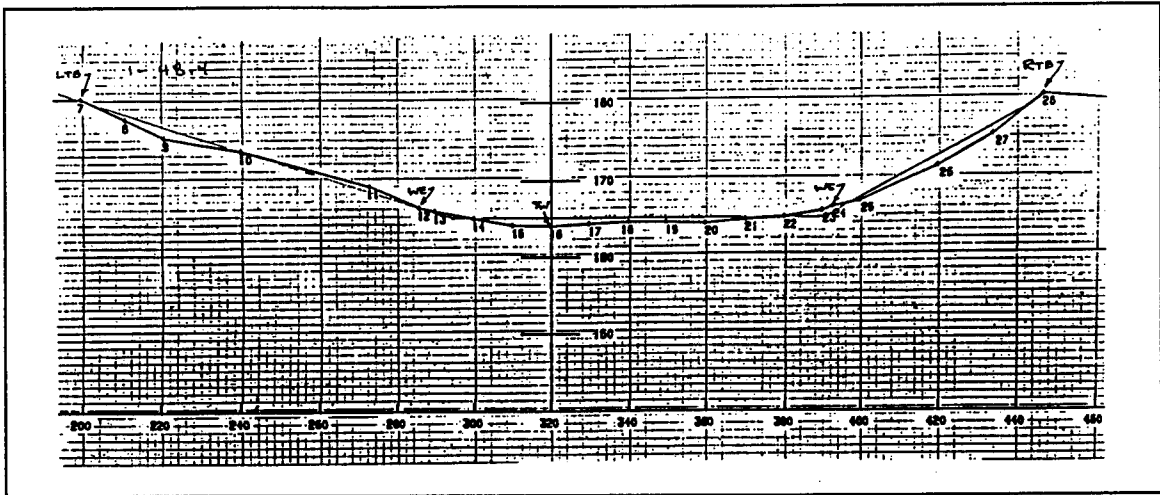


Figure A1. Cache River cross section #1, river mile 48.4

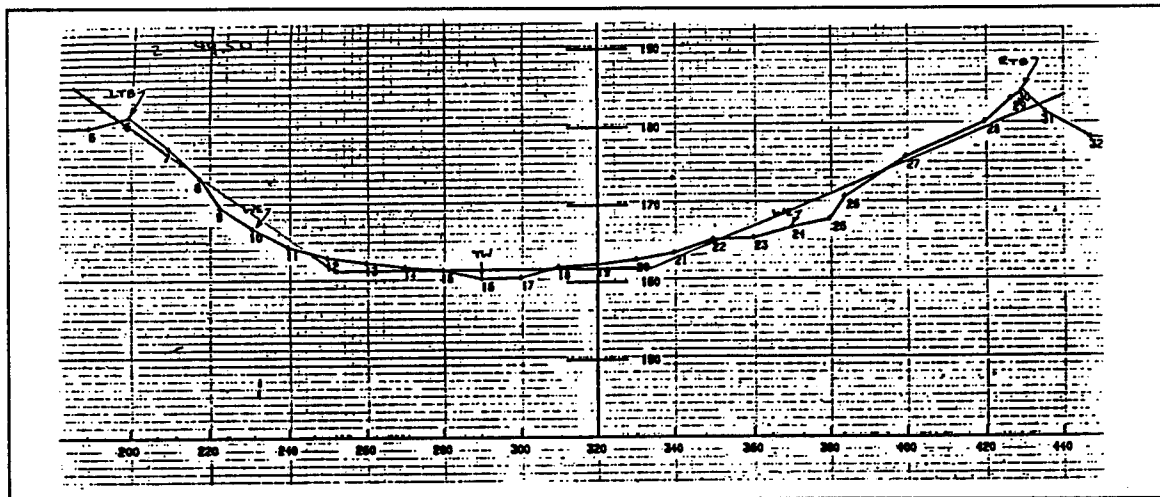


Figure A2. Cache River cross section #2, river mile 49.5

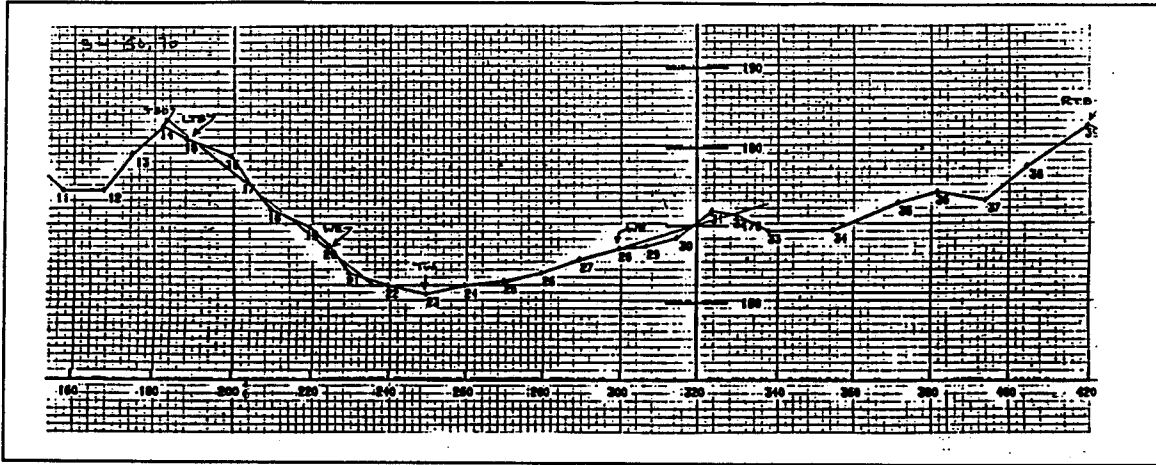


Figure A3. Cache River cross section #3, river mile 50.7

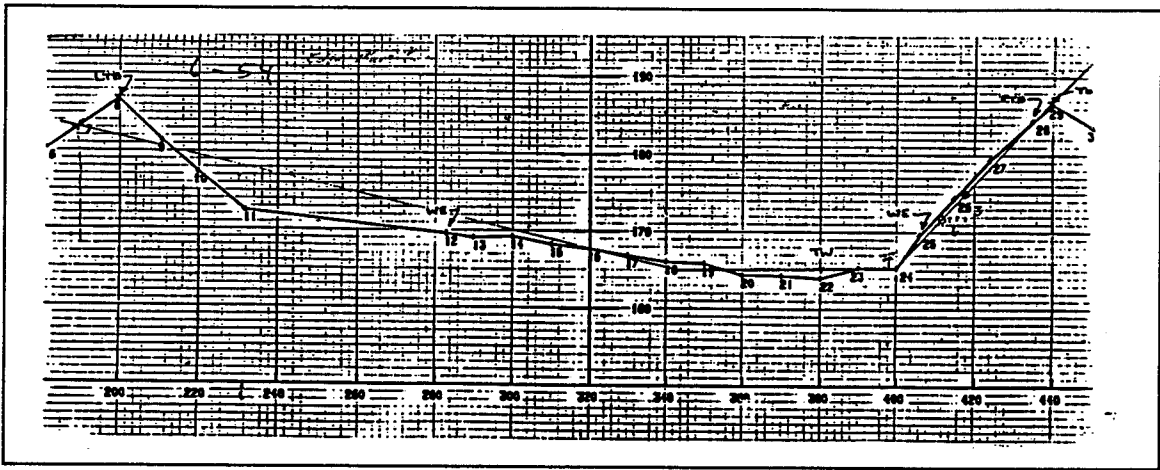


Figure A4. Cache River cross section #4, river mile 51.5

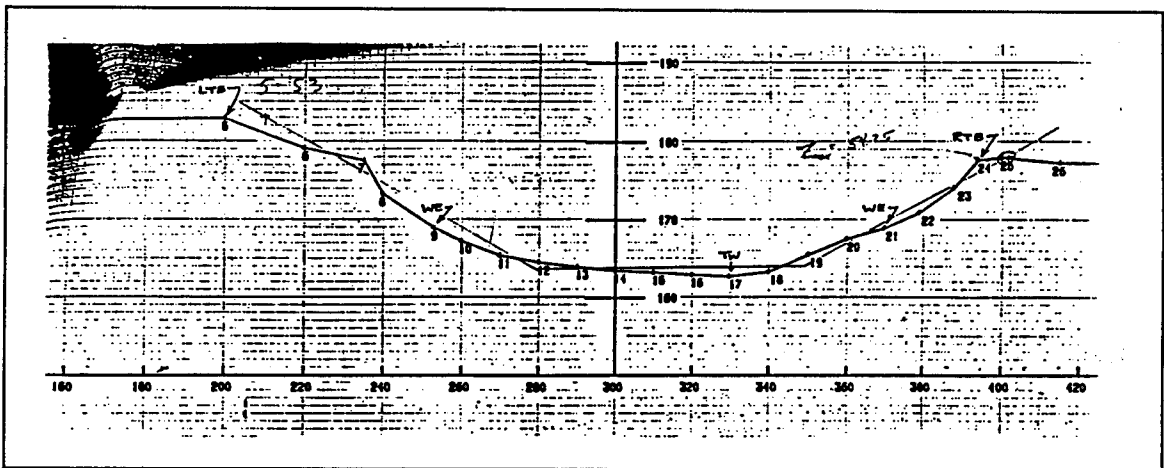


Figure A5. Cache River cross section #5, river mile 53.0

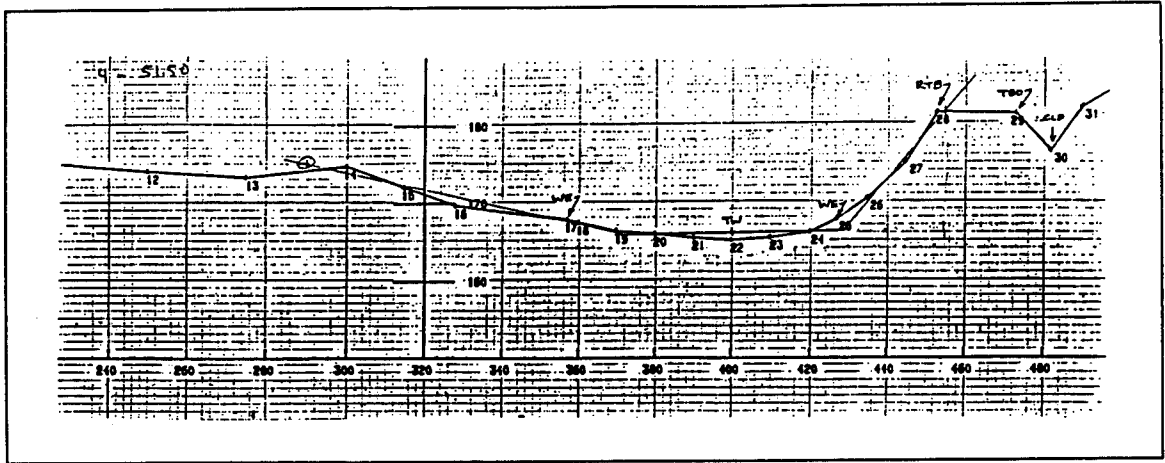


Figure A6. Cache River cross section #6, river mile 54.0

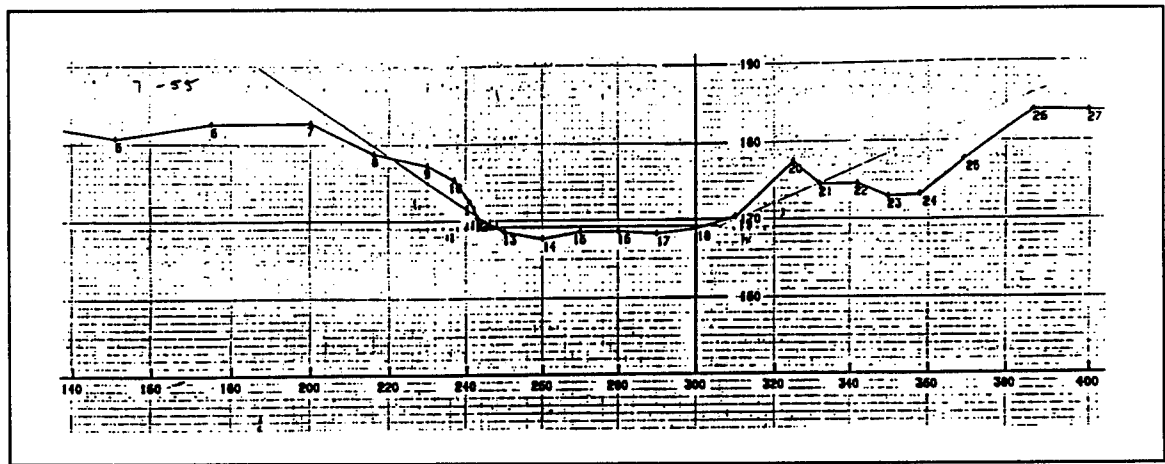


Figure A7. Cache River cross section #7, river mile 55.0

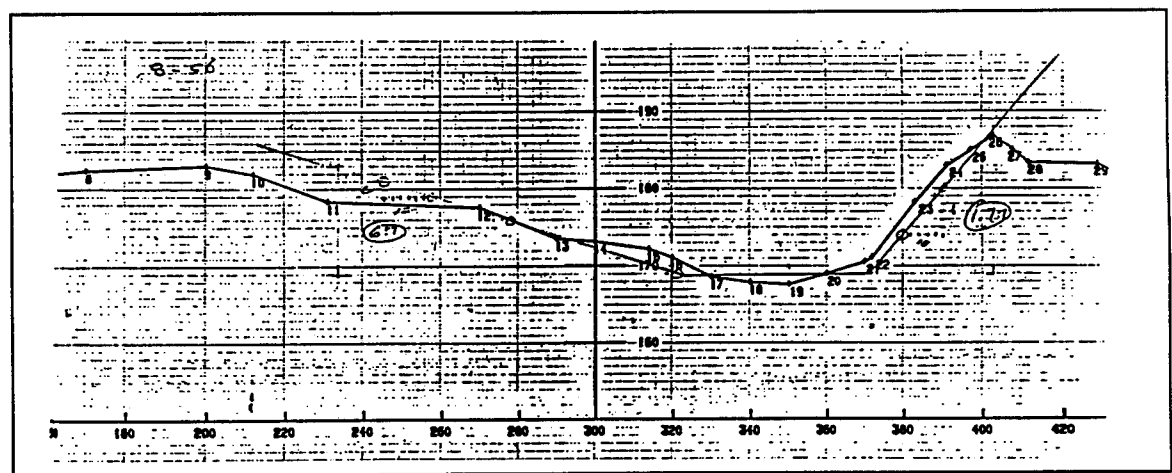


Figure A8. Cache River cross section #8, river mile 56.0

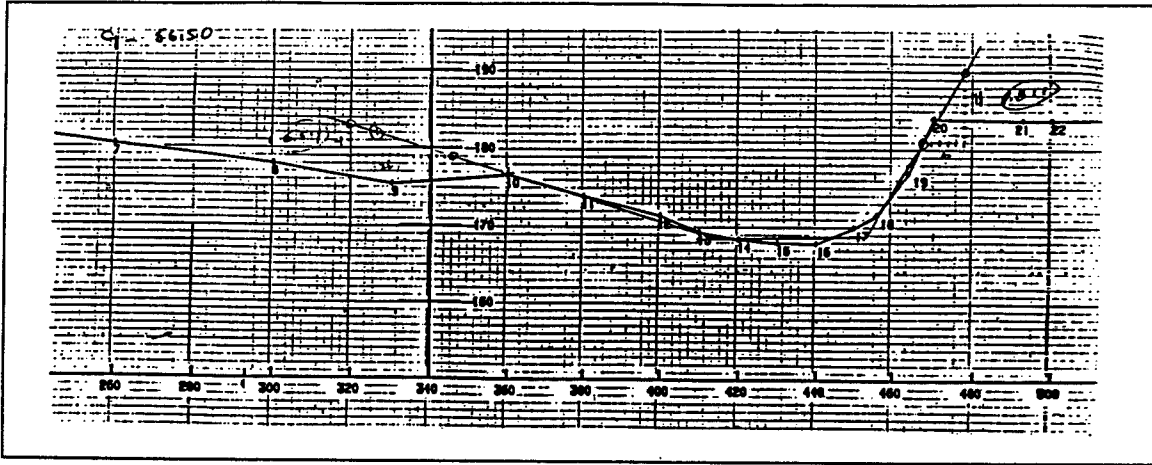


Figure A9. Cache River cross section #9, river mile 56.5

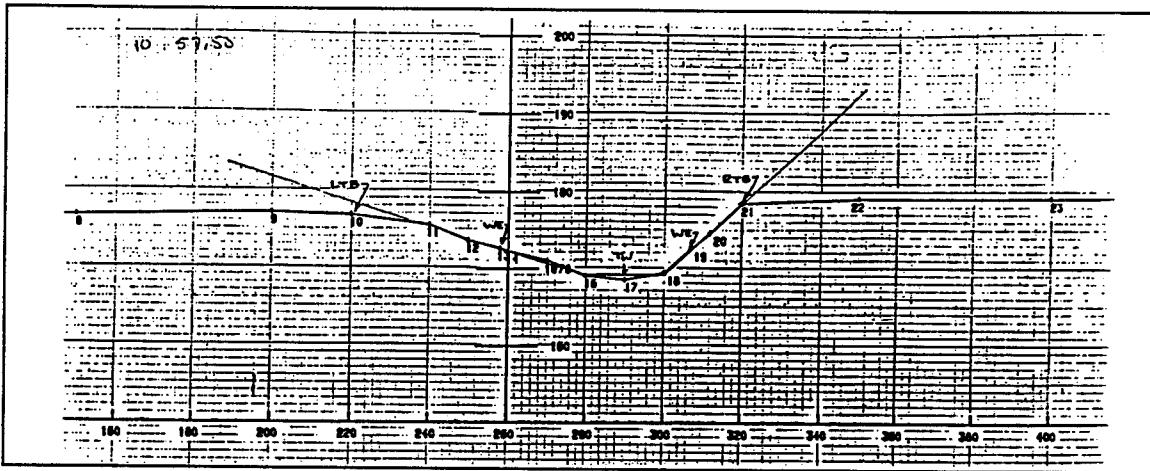


Figure A10. Cache River cross section #10, river mile 57.5

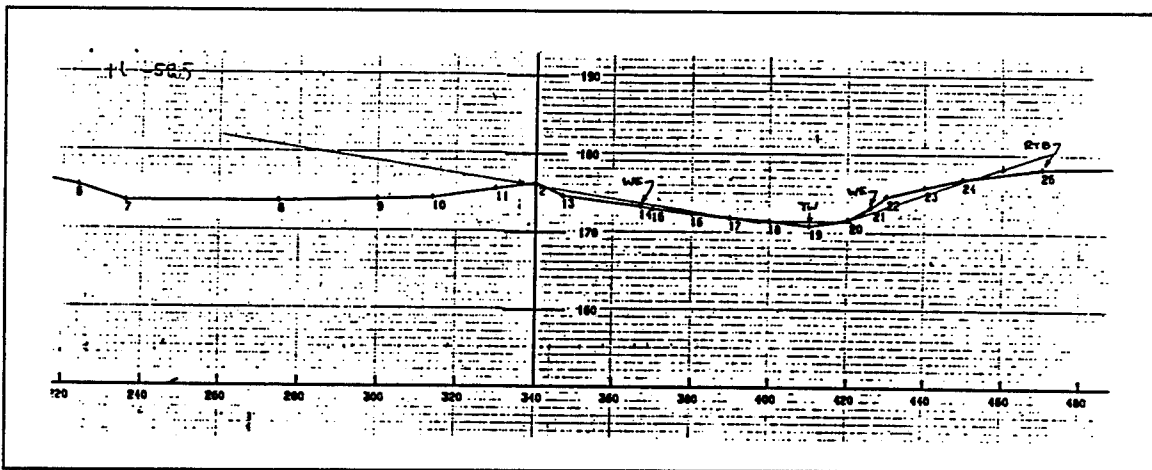


Figure A11. Cache River cross section #11, river mile 58.5

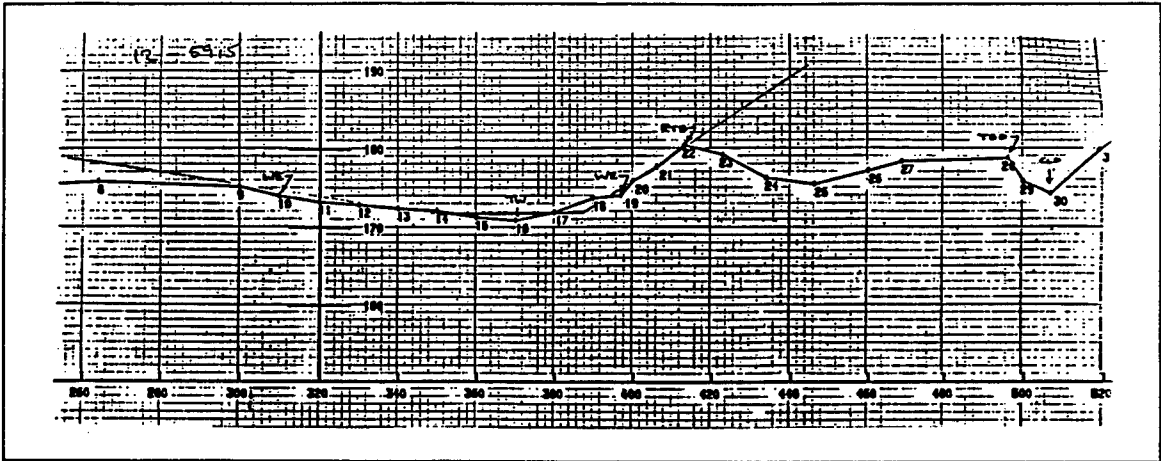


Figure A12. Cache River cross section #12, river mile 59.5

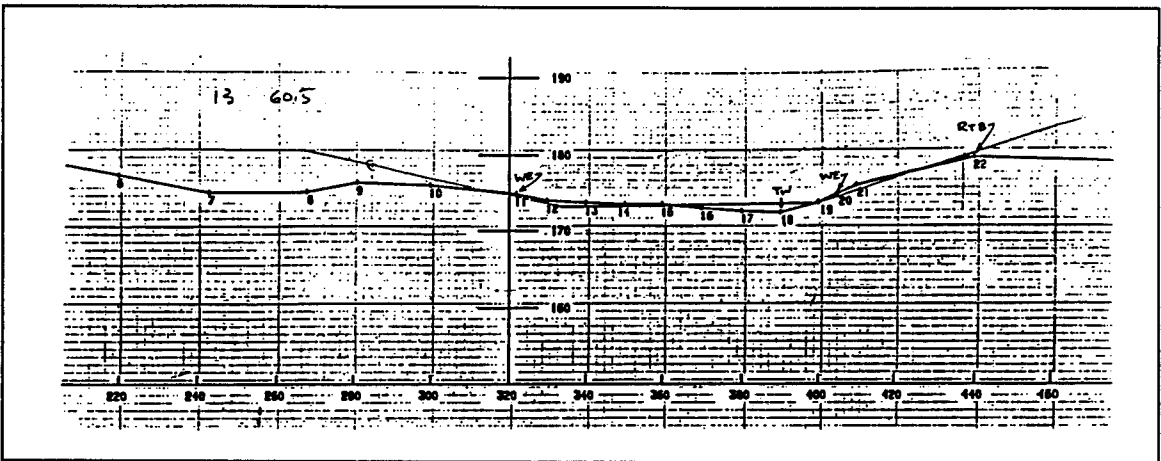


Figure A13. Cache River cross section #13, river mile 60.5

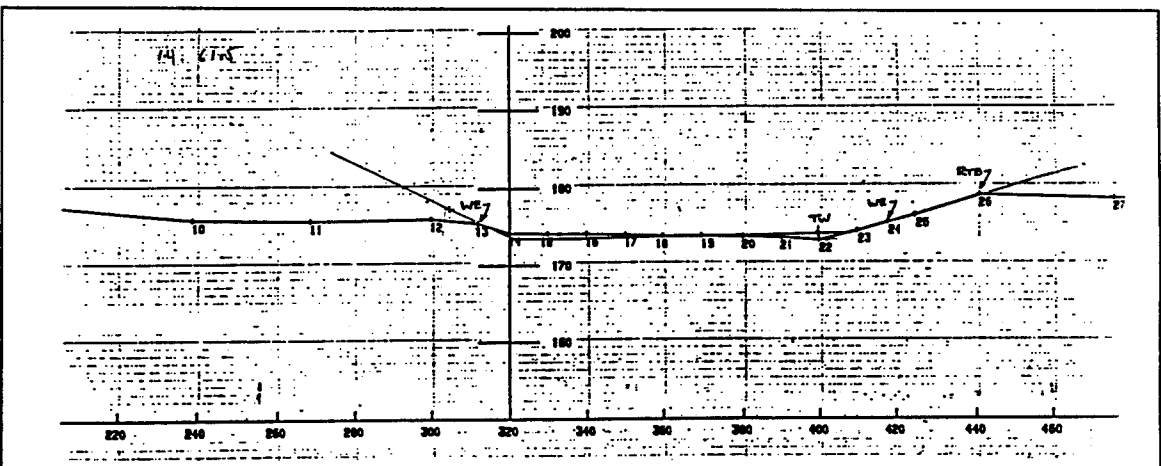


Figure A14. Cache River cross section #14, river mile 61.5

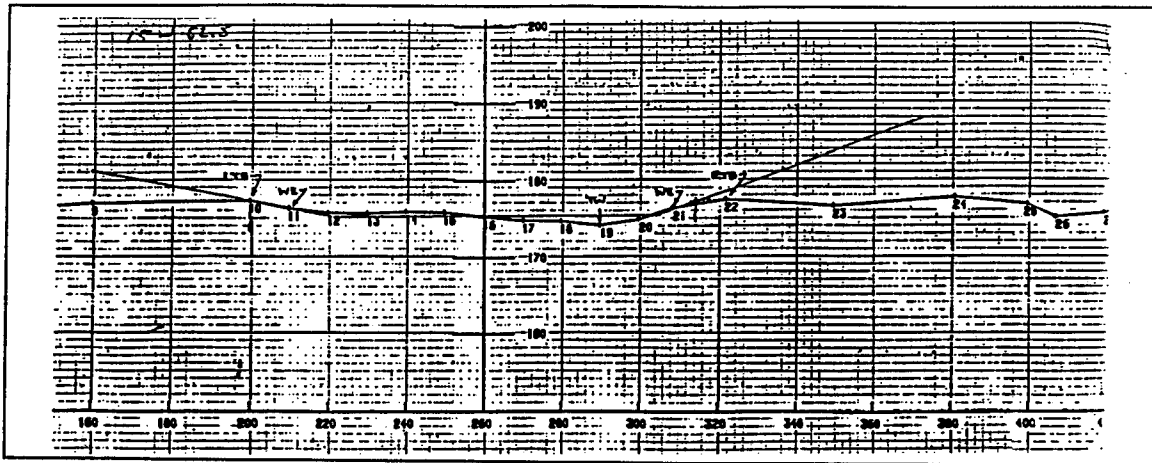


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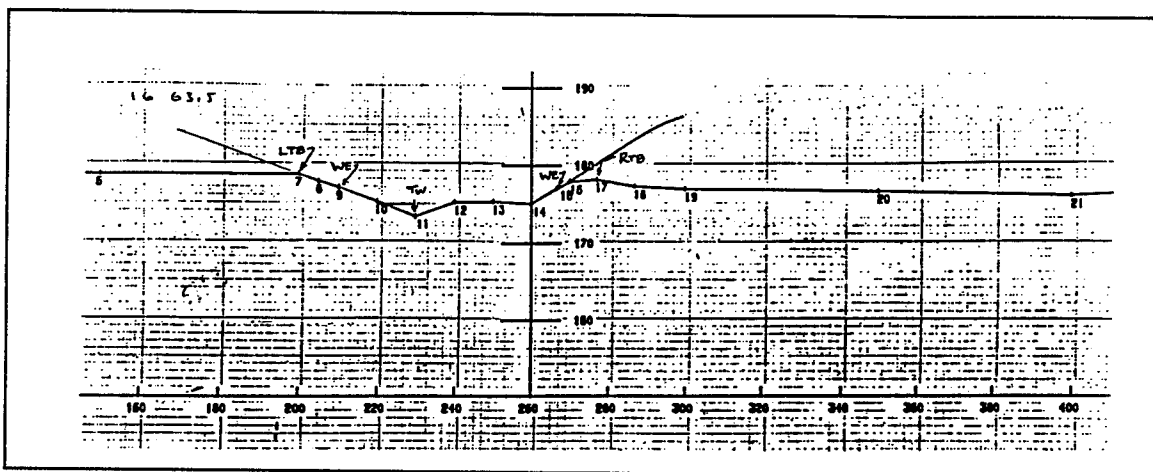


Figure A16. Cache River cross section #16, river mile 63.5

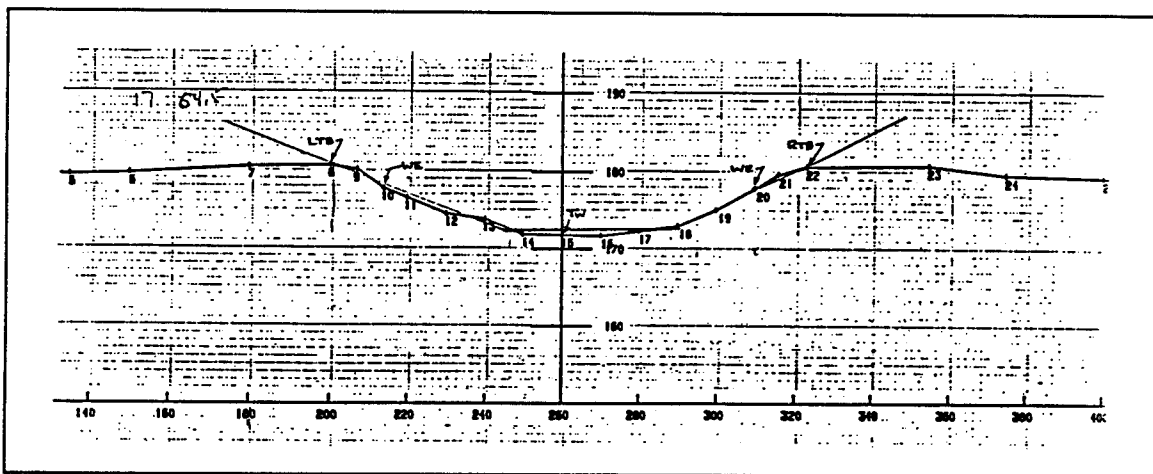


Figure A17. Cache River cross section #17, river mile 64.5

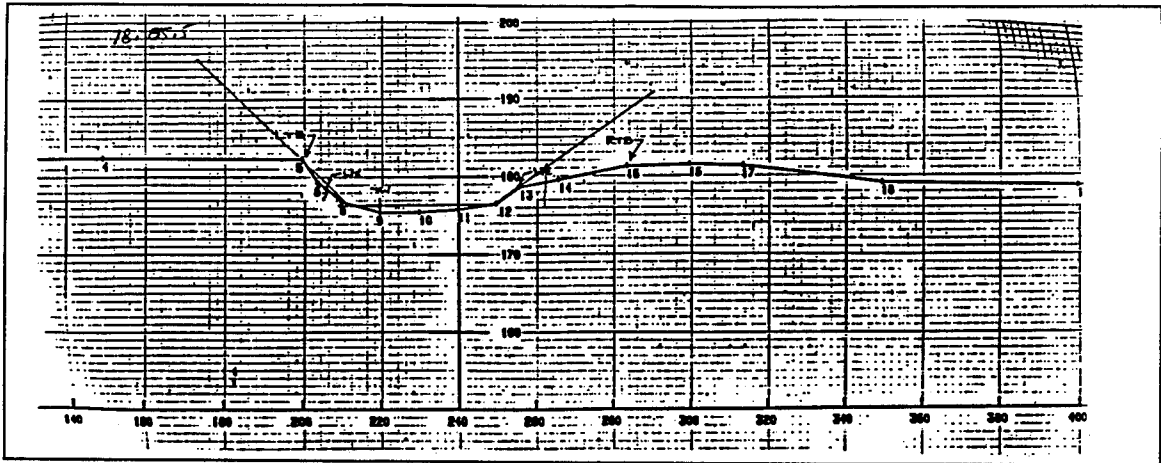


Figure A18. Cache River cross section #18, river mile 65.5

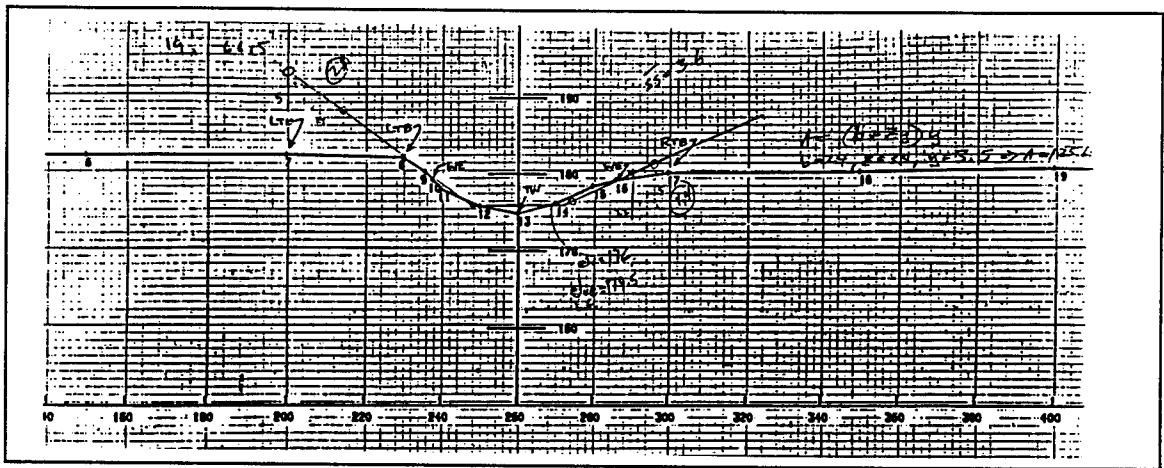


Figure A19. Cache River cross section #19, river mile 66.5

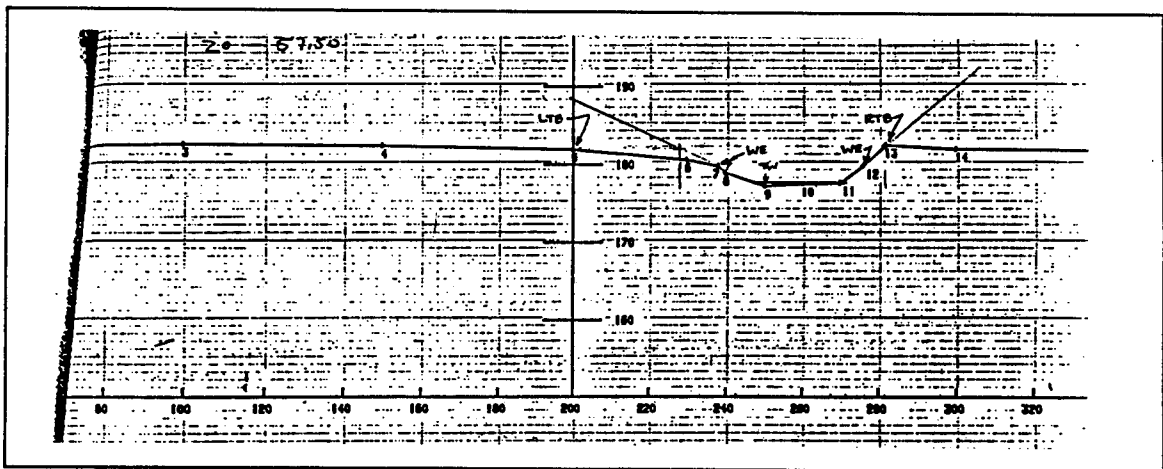


Figure A20. Cache River cross section #20, river mile 67.5

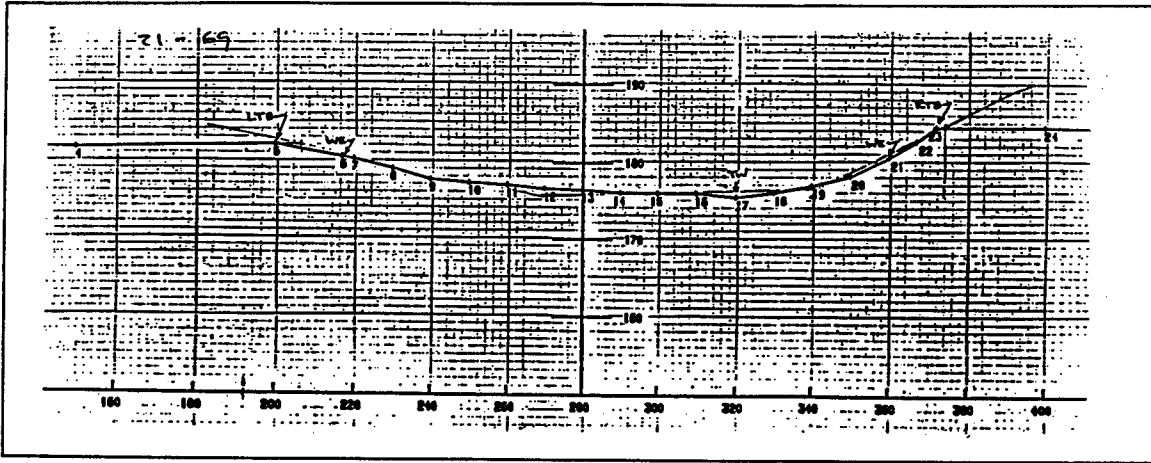


Figure A21. Cache River cross section #21, river mile 69.0

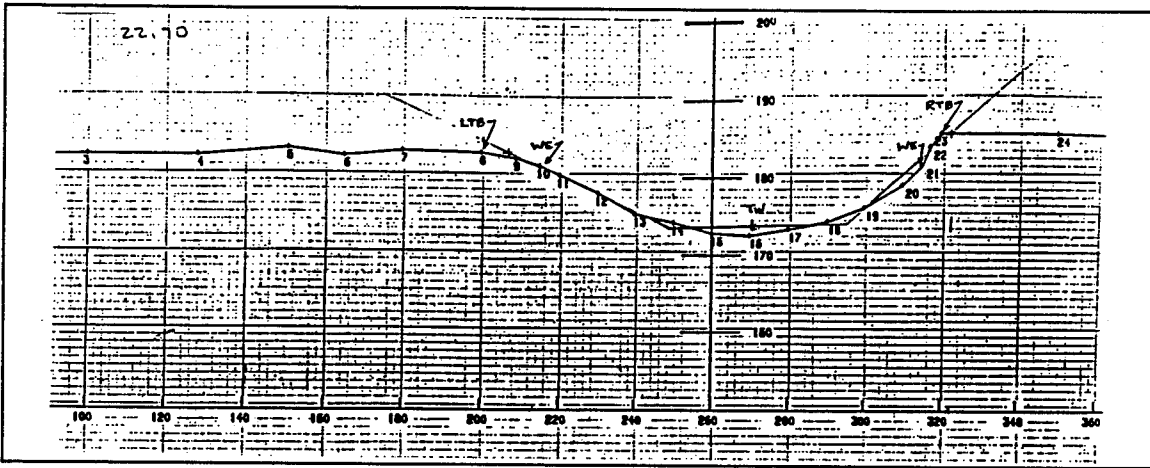


Figure A22. Cache River cross section #22, river mile 70.0

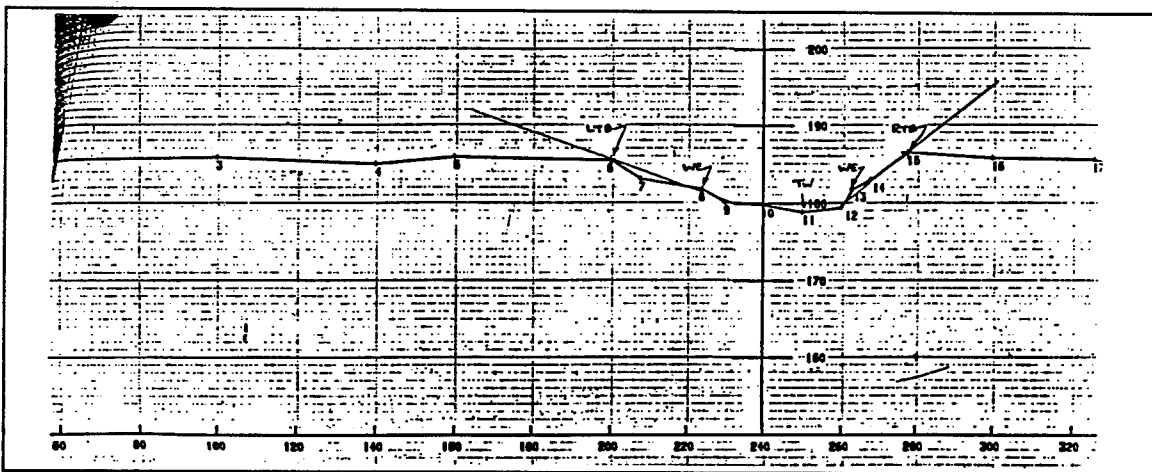


Figure A23. Cache River cross section #23, river mile 71.0

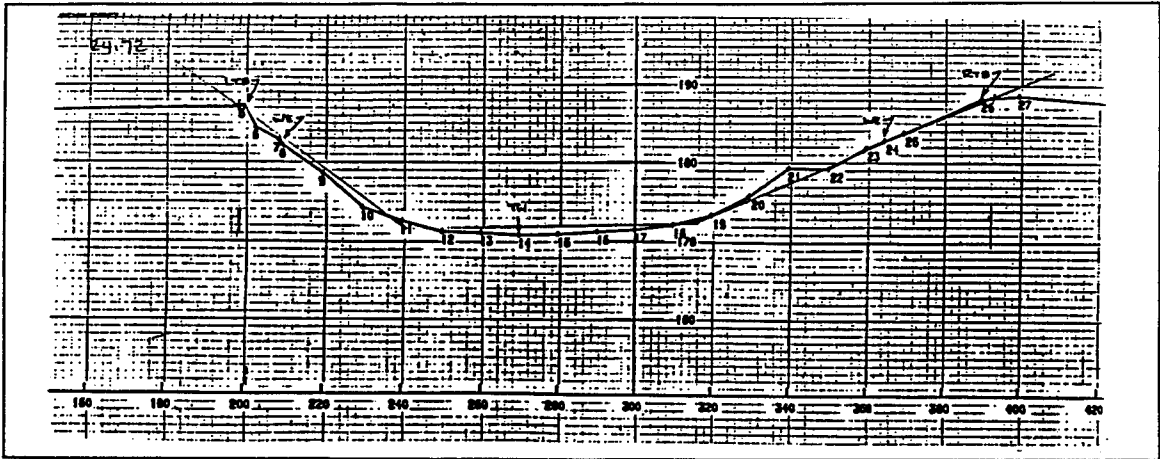


Figure A24. Cache River cross section #24, river mile 72.0

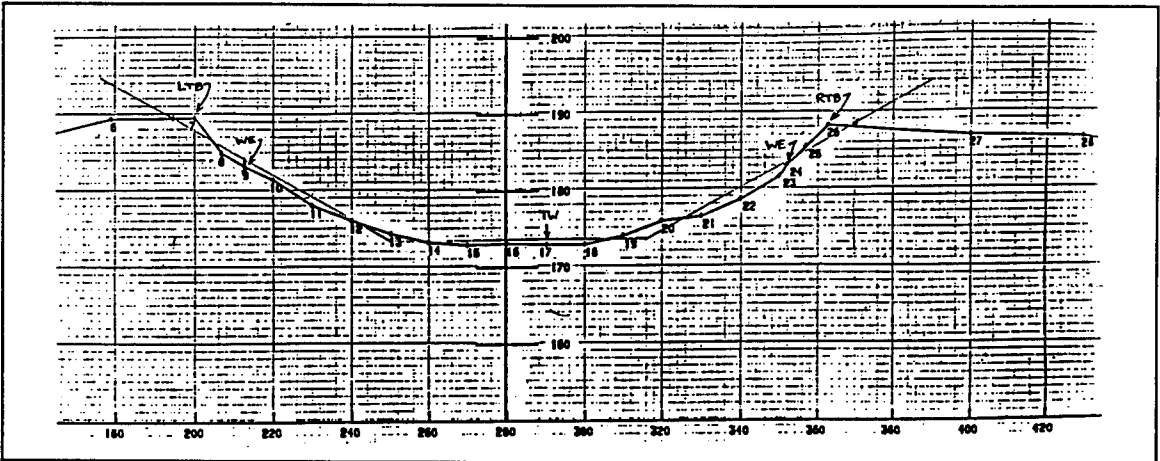


Figure A25. Cache River cross section #25, river mile 73.0

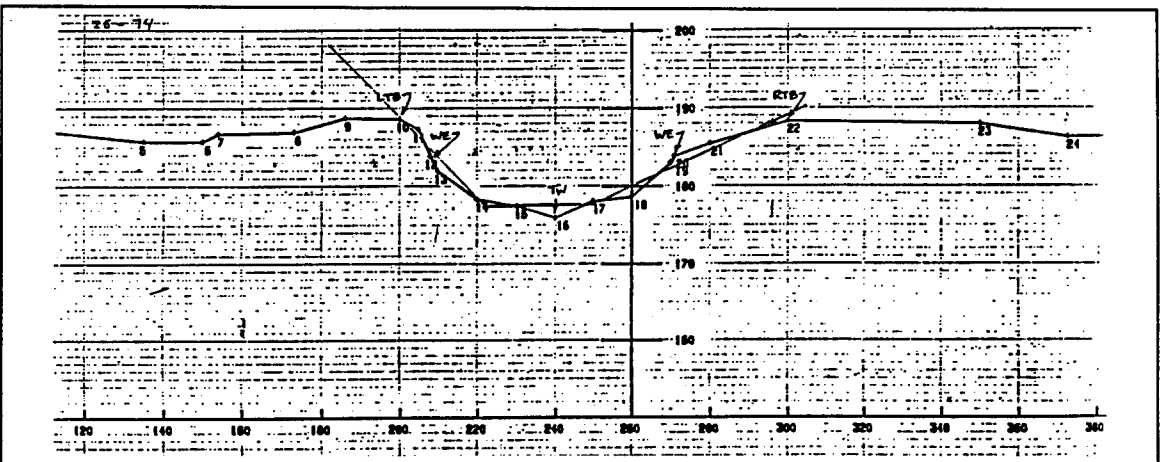


Figure A26. Cache River cross section #26, river mile 74.0

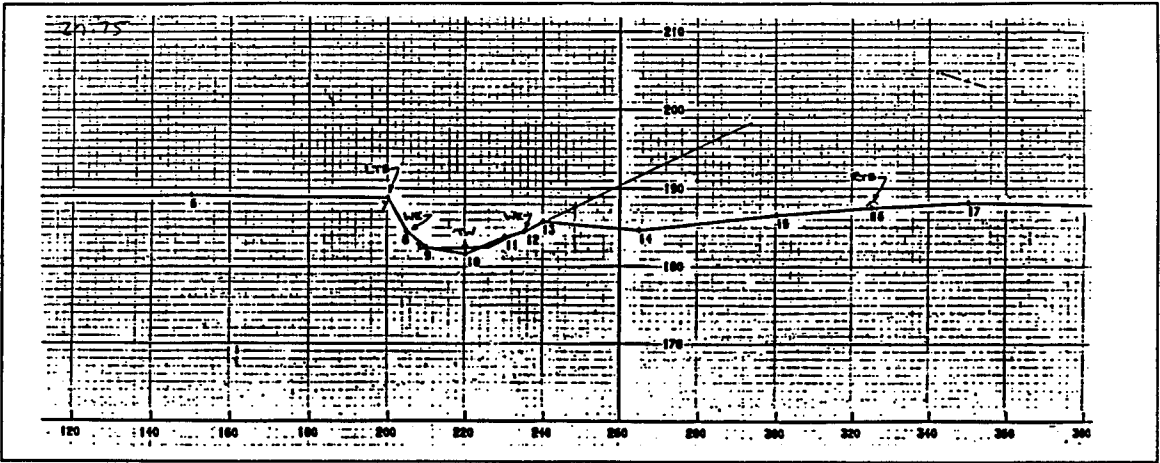


Figure A27. Cache River cross section #27, river mile 75.0

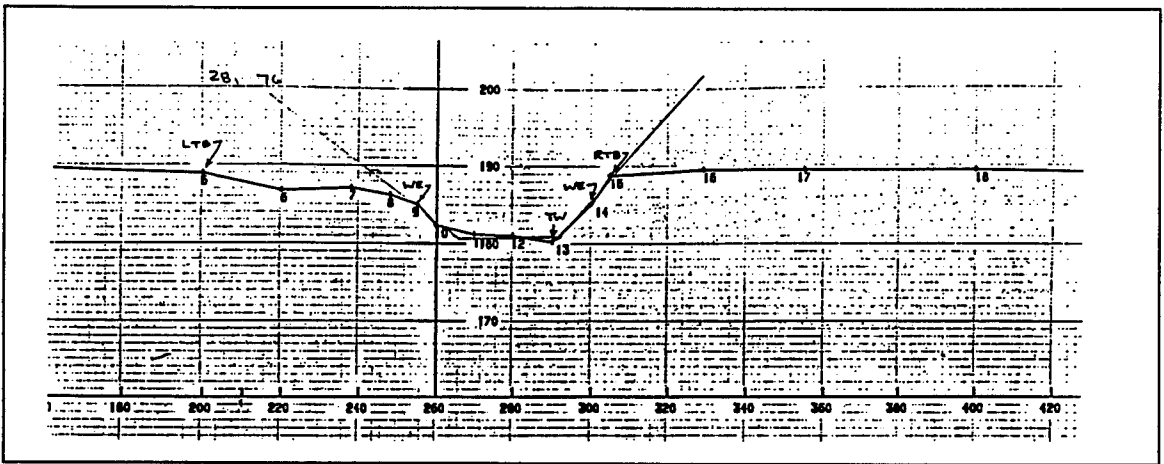


Figure A28. Cache River cross section #28, river mile 76.0

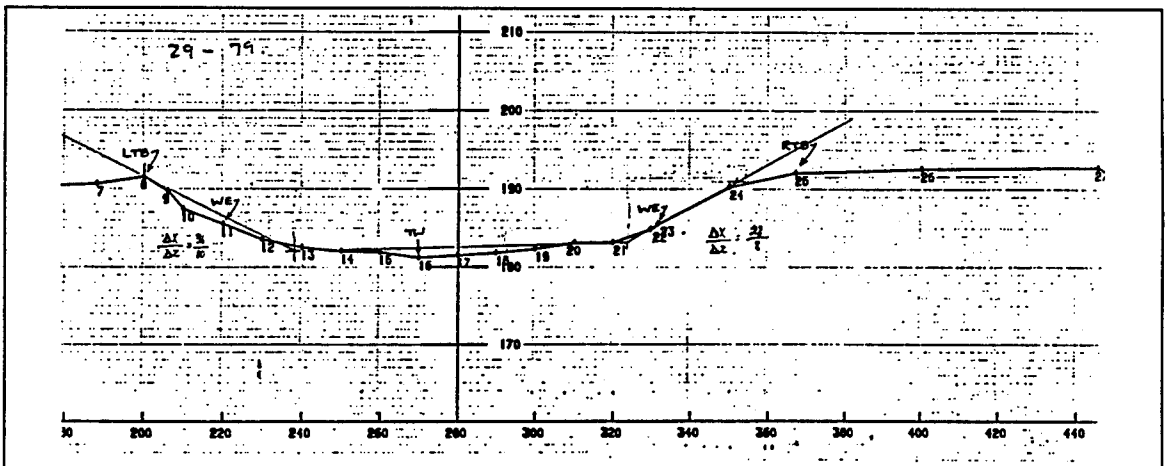


Figure A29. Cache River cross section #29, river mile 79.0

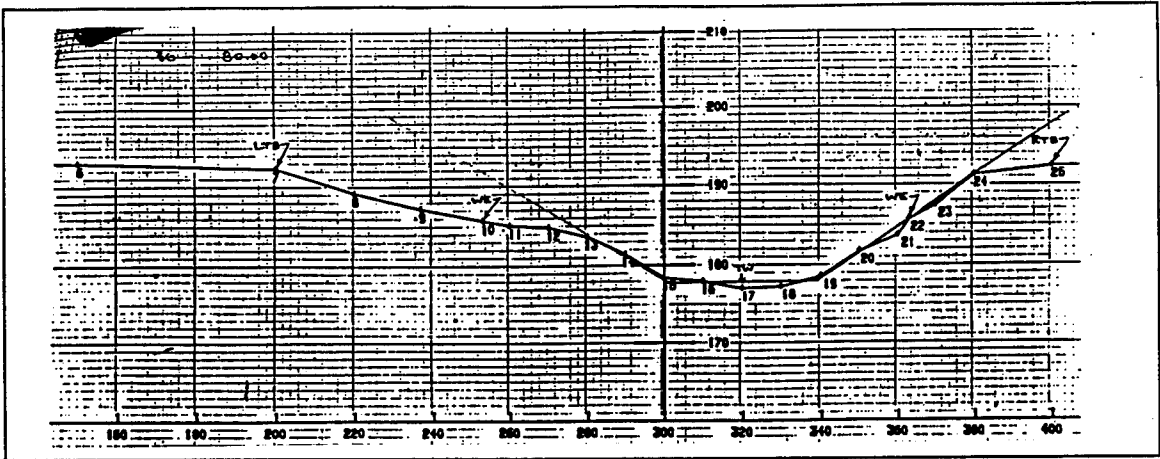


Figure A30. Cache River cross section #30, river mile 80.0

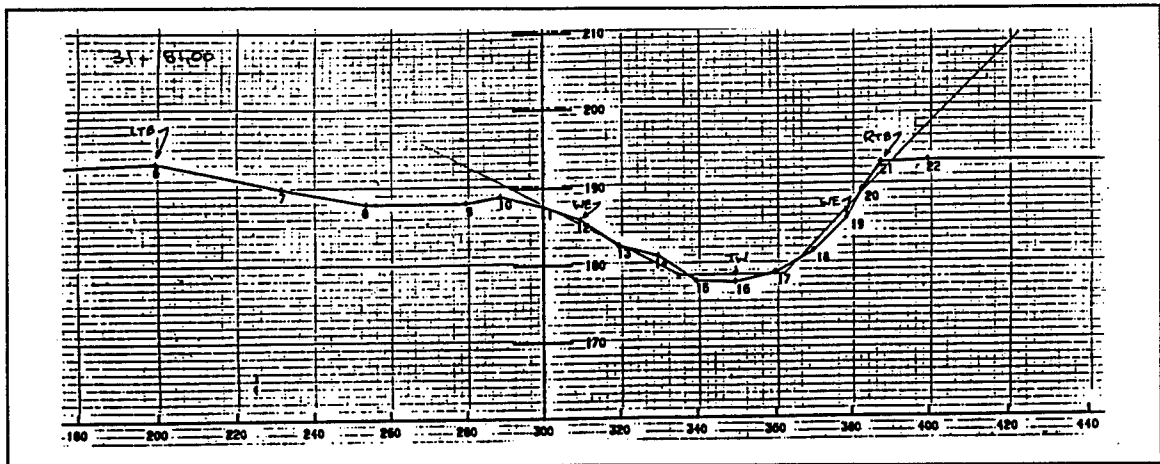


Figure A31. Cache River cross section #31, river mile 81.0

REPORT DOCUMENTATION PAGE

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6. AUTHOR(S) Raymond Walton, Raymond S. Chapman, Thomas H. Martin, Jack E. Davis
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Engineer Waterways Experiment Station 3909 Halls Ferry Road, Vicksburg, MS 39180-6199	8. PERFORMING ORGANIZATION REPORT NUMBER Technical Report WRP-CP-6
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13. ABSTRACT (Maximum 200 words) We investigated hydrologic characteristics of the Cache River wetland between Patterson and Cotton Plant, AR. The Cache River is an underfit stream with wetlands predominantly located in abandoned channels and backswamps. Much of the Cache River upstream of the study area has undergone extensive channelization to allow agricultural development in the basin. Hydrologic measurements included U.S. Geological Survey river gauges at the upstream and downstream limits of the study area (40 river km apart), water level recorders inside the study area, a nest of deep and shallow groundwater wells that monitored variations in the underlying aquifer, a meteorological recording station that collected precipitation, air temperature, and solar radiation data inside the study area, and regional precipitation data. Analysis of the wetland's water budget showed that the system is dominated by river flows and the magnitudes of the other water budget components fall within the error of well maintained river gauges (5 to 10 percent). The system is characterized by the floods occurring from late-fall to late winter and again in mid- to late spring. Peak flood flows are approximately 185 m ³ /s for a 2-year return event and 270 m ³ /s for a 5-year event. Peak flows between the upstream and downstream gauges are reduced by 10 to 20 percent with greater attenuation (Continued)

14. SUBJECT TERMS See reverse.	15. NUMBER OF PAGES 118
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13. (Concluded).

occurring when the system is initially drier. Peak flow at the downstream gauge lags the peak at the upstream gauge by 4 to 8 days depending on the antecedent conditions. Flooding of the overbank areas is a result of constrictions in the downstream reaches of the study area. Flood-peak attenuation between the upstream and downstream gauges is due mainly to floodplain storage with flow resistance contributing minimally.

A Wetlands Dynamic Water Budget Model was developed and applied to support the field investigation. The model augmented the field study's measured hydrologic data by filling data gaps that occurred due to gauge problems and by providing simulated data for broad areas of the wetland, particularly those far away from any measurement station. The model includes three dynamically linked modules to account for all the major components of a typical water budget, including precipitation, canopy interception, overland flow, channel flow, infiltration, evapotranspiration, and saturated groundwater flow. The model is called the Wetlands Dynamic Water Budget Model because it provides magnitudes for the water budget components, as well as water depths, discharges, and flow velocities over different parts of the modeled system. The development of the computer program is based on concepts and approaches of a number of programs in common use. The model was used to simulate various wetland modification scenarios to help build an understanding of how wetlands, like those along the Cache River, function hydrologically. Scenarios included creating various types of constrictions across the wetland, such as might occur with the construction of a highway crossing, channelizing the river by installing levees on the overbanks, and creating wider floodplains by restoring agricultural lands to wetland habitat.

14. Subject Terms.

Bottomland hardwood
Canopy interception
Channel flow
Evapotranspiration
Field study
Groundwater flow
Hydraulics
Hydrologic cycle
Hydrology
Infiltration
Model
Overland flow
Simulation
Water budget
Wetlands